UNITED NATIONS FOOD SYSTEMS SUMMIT 2021

The Scientific Group for the UN Food System Summit

sc-fss2021.org

SCIENCE AND INNOVATIONS

for Food Systems Transformation and Summit Actions

Joachim von Braun, Kaosar Afsana,
Louise O. Fresco, Mohamed Hassan (editors)

Papers by the Scientific Group and its partners in support of the UN Food Systems Summit.

TABLE OF CONTENTS

(The full list of authors on the cover page of the paper.)

VI. COSTS, INVESTMENT, FINANCE, AND TRADE ACTIONS

VII. STRATEGIC PERSPECTIVES AND GOVERNANCE

MEMBERS OF THE SCIENTIFIC GROUP

Joachim von Braun (Germany)
Chair of the Scientific Group, Director of the Center for Development Research (ZEF), Bonn University, and Professor for economic and technological change.

Kaosar Afsana (Bangladesh)
Vice Chair of the Scientific Group, BRAC James P Grant School of Public Health, BRAC University, Dhaka.

Louise Fresco (Netherlands)
Vice Chair of the Scientific Group, President of the Executive Board, Wageningen University & Research.

Mohamed Hassan (Sudan)
Vice Chair of the Scientific Group, President of The World Academy of Sciences for the advancement of science in developing countries (TWAS).

Mario Herrero Acosta (Costa Rica)
Chief Research Scientist of Agriculture and Food, The Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Ousmane Badiane (Senegal)
Chairperson of Akademiya2063, former Africa Director for the International Food Policy Research Institute (IFPRI).

Patrick Caron (France)
Vice President of the University of Montpellier, President of Agropolis International and Director of the Montpellier Advanced Knowledge Institute on Transitions.

Martin Cole (Australia)
Chairperson of the HLPE Steering Committee of CFS. Professor and Head of School of Agriculture, Food and Wine at University of Adelaide.

Ismahane Elouafi (Morocco / Canada)
Chief Scientist of the Food and Agriculture Organization (FAO) of the United Nations.

Frank A. Ewert (Germany)
Scientific Director, Leibniz Centre for Agricultural Landscape Research (ZALF).

Sheryl L. Hendriks (South Africa)
Professor of Food Security & Director, Institute for Food, Nutrition and Well-being, University of Pretoria.

Thomas W. Hertel (USA)
Professor of Agricultural Economics at Purdue University and Executive Director of the Global Trade Analysis Project (GTAP).

Jikun Huang (China)
Professor at School of Advanced Agricultural Sciences and Director of China Center for Agricultural Policy (CCAP), Peking University.

Marta Hugas (Spain)
Chief Scientist at European Food Safety Authority (EFSA).

Elizabeth Hodson de Jaramillo (Colombia)
Professor Em. School of Sciences of the Pontificia Universidad Javeriana, and member of Inter American Network of Academies of Sciences (IANAS).

Andrew Kambugu (Uganda)
Executive Director Infectious Diseases Institute (IDI), College of Health Sciences, Makerere University. Co-founder of the Researchers for Global Health (R4GH) initiative.

Kaoru Kitajima (Japan)
Professor at Kyoto University Graduate School of Agriculture; a forest ecologist, especially in tropical America and Asia.

Rattan Lal (India)
Professor of Soil Science, Director of the Carbon Management and Sequestration Center at Ohio State University. World Food Prize Laureate 2020.

Uma Lele (India)
President of the International Association of Agricultural Economists (IAAE).

Lynnette M. Neufeld (Canada)
incoming President of the International Union of Nutrition Scientists (IUNS), Director Knowledge Leadership, Global Alliance for Improved Nutrition (GAIN).

Urs Niggli (Switzerland)
Scientist focusing on sustainable farming systems, from 1990 to 2020 he led the Research Institute of Organic Agriculture (FiBL).

Claudia Sadoff (USA)
Executive Management Team Convener and Managing Director, Research Delivery and Impact, of the Consultative Group on International Agricultural Research.

Lisa Sennerby Forsse (Sweden)
past President, Royal Swedish Academy of Agriculture and Forestry (KSLA) and was the vice-chancellor of the Swedish University of Agricultural Sciences 2006-2015.

Jean-François Soussana (France)
Vice-President of International Policy at the Institute national de la recherche agronomique (INRAE).

Morakot Tanticharoen (Thailand)
Professor and Senior Advisor to the President of the National Science and Technology Development Agency (NSTDA), research in microbiology and biotechnology.

Maximo Torero (Peru)
Ex-officio member of Scientific Group Chief Economist of the Food and Agriculture Organization of the United Nations (FAO).

Aman Wirakartakusumah (Indonesia)
Professor Em. at Department of Food Science and Technology and Senior Scientist at SEAFAST Center, Bogor Agricultural University (IPB), President-Elect of the International Union of Food Science and Technology.

David Zilbermann (Israel, USA)
Professor in the Department of Agricultural and Resource Economics, University of California at Berkeley. One of the Founders of the International Consortium of Applied Bio-economy Research (ICABR)

FOREWORD

by Agnes Kalibata Special Envoy for UN Food Systems Summit

The UNFSS Scientific Group (ScGroup) was responsible to bear the foremost scientific evidence to the United Nations 2021 Food Systems Summit by helping stakeholders and participants to access shared knowledge about experiences, approaches, and tools for driving sustainable food systems. Led by Professor Joachim von Braun and three Vice Chairs, this committee of twenty-eight experts from diverse backgrounds around the world, was mandated from the Deputy Secretary-General of the United Nations (see ToR here) to deep into their huge institutional networks to bring forth their expertise, access progress and make and recommendations on science-based approaches to achieving SDGs while clearly bringing out trade-offs associated with Food System Transformation.

One of the key roles for the ScGroup was to bring to the summit diverse viewpoints through its networks of partners from all regions of the world to ensure inclusion of diversity of frameworks and regions, and link science-based syntheses with ongoing initiatives under inter alia, the UN system, the CFS High Level Panel of Experts, the CGIAR, Science-based institutions and any other relevant knowledge that will help advance the quality of evidence for future food systems. The group has thus held monthly meeting since July 2020 July 2021, generally in Rome, or connected via teleconference to determine approaches and collect views from their networks. All the presentations and minutes of these key meetings are available here.

One of the key deliverable is a reference paper about concepts and definitions of food systems and determinations of their change entitled "Food Systems Definition, Concept and Application for the UN Food Systems Summit" to inform the public and stakeholders interested in the Food Systems Summit. A second strategic paper on "Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit" identifies seven science-driven innovations that must be pursued in an integrated manner for a successful transformation of the food systems. It focuses on the key role of science and research, as they are essential for innovations that accelerate the transformation to healthier, more sustainable, equitable, and resilient food systems.

The third key deliverable is a set of invited Food Systems Summit Briefs papers in support of the Summit agenda setting and authored by researchers in the Partner organizations and members of the ScGroup. They are structured through the following 6 topics:

(i) Modelling Food Systems Transformations (3 briefs)

(ii) Science, Technology, and Innovation Actions (8 briefs)

(iii) Actions for Equity, Inclusiveness and Nutrition and Health (11 briefs)

(iv) Actions for Sustainable Resource Use and Foresight (8 briefs)

(v) Investment, Finance, Trade and Governance actions (3 briefs)

(vi) Actions in Regions and Countries (9 briefs)

Finally, after this 1-year contribution, the ScGroup has helped to ensure the robustness and independence of the science underpinning dialogue of food system policy and investment decisions and to focus on driving progress towards the SDGs. And it was agreed that the ScGroup would continue informing the Summit's outcomes and clarify science-informed commitments that will emerge from the Summit for further implementations at national, regional and global levels.

The work and contribution of the Scientific group of the Summit has provided incredible direction on how we move forward from here. There will always be need for new evidence, there will always be need to sharpen the Science /Policy/Action interface and I am grateful that this gets the steer we need to move forward a food systems approach to the way we produce, use and manage food.

INTRODUCTION

by Joachim von Braun Chairperson Scientific Group for the UN Food Systems Summit

This Reader reports about the findings of the Scientific Group of the UN Food Systems Summit (ScGroup) along with selected briefs prepared by its global partners. The ScGroup is an independent group of leading researchers and scientists from around the world with a **mandate from the Deputy Secretary-General of the United Nations** as follows: "The Scientific Group is responsible for ensuring that the Summit brings to bear the foremost scientific evidence from around the world and helps expand the base of shared knowledge about experiences, approaches, and tools for driving sustainable food systems that will inform the future. The work of the Scientific Group ensures the robustness and independence of the science underpinning dialogue of food systems policy and investment decisions. It also informs the content of the Summit, its recommended outcomes, and the asks and commitments that emerge from the Summit." (see Annex 1 for the Deputy Secretary General's Letter of April 13, 2020). These papers and briefs bring science- and research-based, state-of-the-art, solution-oriented knowledge and evidence to inform transformation of the contemporary food systems to achieve more sustainable, equitable and resilient food systems. The ScGroup papers included in this Reader have been peer-reviewed and they have been further scrutinized by governments, civil societies, and members of the general public. The inclusive approach of the ScGroup has resulted in the various drafts of these papers being distributed widely.

In addition, the ScGroup brings to the summit diverse viewpoints through its **networks of partners from all regions** of the world who contributed more than 40 briefs (see Annex 2 for complete list). Research partners of the ScGroup were selected on the basis of their commitment to rigorous scientific research and the diversity of their knowledge frameworks and regional coverage. ScGroup members served as commentators and reviewers of the partner briefs. Due to size limitations, only a selection of the Partner briefs could be included in this Reader; this is not a reflection on the quality of these submissions.

The Reader is divided into seven sections. While the volume is organized by themes, the papers and briefs recognize the interdependence of food, health, environment systems and emphasize capitalizing on this interdependence through identifying synergies to identify innovations – technological, policy, and institutional -- that can help achieve multiple SDGs.

Section I presents a strategic paper prepared by the leadership of the ScGroup that identifies seven science-driven innovations that *must* be pursued in an integrated manner for a successful transformation of the food systems. The paper calls on national and global policymakers to work hand in hand with the public- and private-sector scientists, academia, civil societies, and with grassroots organizations of marginalized groups including women, and youth. Strategic propositions in the paper include 1) strengthening research cooperation between science communities and Indigenous Peoples knowledge communities, 2) calling on governments to spend at least 1% of food systems GDP on food systems science, and 3) establishing pathways toward strong science - policy interfaces at national and international levels to enable evidence-based follow up to action agendas established at the summit.

Section II on Food Systems Concepts expounds on two key concepts that run through the entire volume: food systems and healthy diets. In the first ScGroup paper, *Food Systems – Definition, Concept and Application for the UN Food Systems Summit,* the authors define food systems and elaborate on the mechanisms for its change. The second ScGroup paper, *Healthy Diet: A Definition for the United Nations Food Systems Summit 2021,* suggests approaches for operationalizing definitions into specific food-based guidance in varied economic, cultural, and social contexts.

Section III deals with Actions on Hunger and Healthy Diets. In a ScGroup paper, *Ensuring Access to Safe and Nutritious Food for All Through Transformation of Food Systems,* a whole-system approach in policy and research (ex-post and ex-ante) to address malnutrition, food safety, poverty and inequality, as well as climate and environmental issues, is recommended. In another ScGroup paper, *Shift to Healthy and Sustainable Consumption Patterns,* various actions to tackle economic and structural costs, challenges to political economy, changes to consumer behavior, inequities and social justice are highlighted. In a Partner brief, *Achieving Zero Hunger by 2030- A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals,* modelling exercises identify synergies between SDG2, SDG1 and SDG3 and potential trade-offs with SDG13 (land for climate), SDG15 (for biodiversity), SDG11 (cities) and SDG6 (water). Another partner brief on *Fruits and vegetables for healthy diets: Priorities for food system research and action* makes the case for research and policies on promoting consumption of fruits and vegetables to improve human health and the environment and for safeguarding biodiversity.

Section IV, Actions for Equity and Resilience in Food Systems, challenges inequalities within food systems and puts forward recommendations for more equitable food systems. The ScGroup paper, *Advance Equitable Livelihoods,* makes a case for rights-based, contextually relevant, integrated, and inclusive long-term national and local programs and investments. Two Partner briefs, *A Review of Evidence on Gender Equality, Women's Empowerment and Food Systems* and *The Future of Small Farms: Innovations for Inclusive Transformation* delineate evidence-based pathways for the inclusion of two key players within the food systems that are marginalized; women and small-holder famers. The ScGroup paper, *Building Resilience to Vulnerabilities, Shocks and Stresses,* presents solutions at multiple scales grounded in the resilience framework that can allow food systems to anticipate, prevent, absorb, adapt to or transform in the face of stresses induced by climate change, population growth and conflicts. The Partner brief on *Addressing Food Crises in Violent Conflicts* emphasizes reduction of food insecurity as a pathway to reduce violent conflicts as well as the reduction of conflicts as a pathway to not exacerbate food crises, and emphasizes that People's rights to food in violent conflicts needs to be assured.

Section V focusses on Actions for Sustainable Resource Management in Food Production Systems. The ScGroup paper on *Boost Nature Positive Production* advances actions and innovations for transforming the current "nature negative" food systems, to food systems that conserve, protect, and regenerate natural resources and the natural environment including biodiversity. Partner briefs address the challenges faced by food systems due to climate change, water scarcity and water pollution in *Climate Change and Food Systems* and *Water for Food Systems and Nutrition.* The somewhat contentious issue of the role of livestock production and consumption in food systems and its health and environmental (un)sustainability is discussed in the Partner brief on *Livestock and Sustainable Food Systems: Status, Trends, and Priority Actions.* The last Partner brief in this section importantly deals with aquatic foods and is titled *The Vital Roles of Blue Foods in the Global Food System*.

Section VI discusses Costs, Investments, Finance and Trade actions needed for the transformation of food systems through four Partner briefs. *Ending Hunger by 2030 – Policy Actions and Costs* reviews and critically appraises the estimated of costs of achieving SDG2. *Financing SGD2 and Ending Hunger* provides financial innovations needed for sustainable investment for food systems transformation. *Trade and Sustainable Food Systems* appraises trade policies that can complement countries' policies for ending hunger and ensuring access to adequate food and nutrition. *True Cost and True Price of Food* estimates the external costs of food systems on health and environment.

In the **Section VII, Strategic Perspectives and Governance** are presented including One-Health, agroecology and bioeconomy approaches with three Partner briefs; *In the age of pandemics, Connecting Food Systems and Health: a Global One Health Approach; Pathways to Advance Agroecology for a Successful Transformation to Sustainable Food Systems;* and *The Bioeconomy and Food Systems Transformation*. The last Partner brief in the Reader, *The Transition Steps Needed to Transform Our Food Systems,* discusses the intermediate steps between the current systems and transformed food systems.

"Science Days" for the UN Food Systems Summit, was an international conference organized by the ScGroup and hosted and facilitated by FAO on July 8 and 9th, with more than 40 side events on July 5-7th (see Annex 2). More than 2,000 participants from research, policy, civil society and industry came together to examine how to unlock the full potential of science, technology, and innovation to transform food systems. They also discussed:

- advancing science-based options for achieving more healthy diets and more inclusive, sustainable and resilient food systems;
- putting science to work, especially through stronger science-policy interfaces, investments in institutional and human capacity, and capitalizing on models and data;
- addressing missed opportunities and contentious issues hindering the advancement of science;
- empowering and engaging key players, including youth, Indigenous Peoples, food industry and start-ups, and women;
- pushing the frontiers of science, especially in bio-science innovations, digital innovations, and policy and institutional innovations;
- looking ahead to the world in 2030 and beyond, and prioritizing urgent actions to achieve Agenda 2030 and the SDGs, especially SDG2.

The ScGroup finds it of great importance that not just its own perspectives, but **the large diverse body of research** of relevance for the UN Food Systems Summit, is acknowledged and utilized for shaping the perspectives of the Summit processes. Therefore a **documentation** of particularly important recent research products and reports has been established on the website of the ScGroup at https://sc-fss2021.org/materials/publications-and-reports-of-relevance-for-food-systems-summit/ It is structured by the food systems concept that was developed be the ScGroup and along the 5 Action Tracks and contains hundreds of important entries.
Adopting the structure of "Action Areas" as currently proposed for the UN Food Systems Summit, which may frame specific "Coalitions of Actions" to implement Food Systems Summit proposals, we present

the research material of the Scientific Group and its Partners matched with these Action Area themes in table 1 below. This shall facilitate a basis for the documented scientific evidence base of the Action Areas, and potential Coalitions, that can be drawn upon in the follow up to the Summit.

This Reader has been assembled to inform discussions at the UN Food Systems Summit and beyond on how science can and must contribute to transformation of food systems. The tremendous support by the Scientific Group members and its Partners with many research organizations and experts who volunteered to contribute their knowledge and expertise is gratefully acknowledged.

Not just individual actions, but the UN Food Systems Summit as a whole must become a game changer. The 1.5 degree global warming goal is equivalent to the zero hunger by 2030 goal. To get there, accelerated science investments and the resulting complex set of innovations need to be one of the priority actions of the Summit. The undernourished, youth, women, Indigenous Peoples, and all those marginalized have the right of agency on all matters of their food systems.

It was a bold decision by the UN leadership to unleash a multi-stakeholder process as well as invite an independent Scientific Group to mobilize science communities around the world and to advise the Summit agenda with science-based evidence. The science communities welcomes that move by the UN, and has become energized to address the complex food systems problems with renewed commitment to identify solutions.

Table 1: Research Reports and Briefs mapped with the UNFSS Areas of Action and Coalitions by the Scientific Group for the UN Food Systems Summit and Research Partners

Action Area	Coalition	Scientific Group Reports & Research Partner Briefs (see https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/ partly multiple entries as some papers cover several Action Areas)
Nourish all people within Planetary Boundaries	• Zero Hunger • Healthy diets from Sustainable Food Systems • Universal School Meals • One Health • Food is Never Waste	1. **Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit** Joachim von Braun, Kaosar Afsana, Louise O. Fresco and Mohamed Hassan 2. **Healthy diet – A definition for the United Nations Food Systems Summit 2021** Lynnette M Neufeld, Sheryl Hendriks, Marta Hugas 3. **Cost and Affordability of Preparing a Basic Meal around the World** William A. Masters, Elena M. Martinez, Friederike Greb, Anna Herforth, Sheryl L. Hendriks 4. **Ensuring Access to Safe and Nutritious Food for All Through Transformation of Food Systems- A Paper on Action Track 1** Sheryl Hendriks, Jean-François Soussana, Martin Cole, Andrew Kambugu, David Zilberman 5. **Shift to Healthy and Sustainable Consumption Patterns- A Paper on Action Track 2** Mario Herrero, Marta Hugas, Uma Lele, Aman Wira, Maximo Torero 6. **Fruits and vegetables for healthy diets: Priorities for food system research and action** Jody Harris, Bart de Steenhuijsen Piters, Stepha McMullin, Babar Bajwa, Ilse de Jager, and Inge D. Brouwer 7. **Safeguarding and using fruit and vegetable biodiversity** Maarten van Zonneveld, Gayle M. Volk, M. Ehsan Dulloo, Roeland Kindt, Sean Mayes, Marcela Quintero, Dhrupad Choudhury, Enoch G. Achigan-Dako, Luigi Guarino 8. **In the age of pandemics, connecting food systems and health: a Global One Health approach** Gebbiena M. Bron, J. Joukje Siebenga, Louise O. Fresco 9. **Reduction of Food Loss and Waste – The Challenges and Conclusions for Actions** Joachim von Braun, Marcelo Sánchez Sorondo and Roy Steiner

Boost Nature Based Solutions and Production	• Agroecology and	1. **Boost Nature Positive Production- A Paper on Action Track 3** Elizabeth Hodson, Urs Niggli, Kaoru Kitajima, Rattan Lal, Claudia Sadoff 2. **The Bioeconomy and Food Systems Transformation** Eduardo Trigo, Hugo Chavarria, Carl Pray, Stuart J. Smyth, Agustin Torroba, Justus Wesseler, David Zilberman, Juan F. Martinez 3. **Safeguarding and using fruit and vegetable biodiversity** Maarten van Zonneveld, Gayle M. Volk, M. Ehsan Dulloo, Roeland Kindt, Sean Mayes, Marcela Quintero, Dhrupad Choudhury, Enoch G. Achigan-Dako, Luigi Guarino 4. **Pathways to Advance Agroecology for a Successful Transformation to Sustainable Food Systems** Urs Niggli, Martijn Sonnevelt, Susanne Kummer 5. **A New Paradigm for Plant Nutrition** Achim Dobermann, Tom Bruulsema, Ismail Cakmak, Bruno Gerard, Kaushik Majumdar, Michael McLaughlin, Pytrik Reidsma, Bernard Vanlauwe, Lini Wollenberg, Fusuo Zhang, Xin Zhang 6. **Water for Food Systems and Nutrition,** Claudia Ringler, Mure Agbonlahor, Kaleab Baye, Jennie Barron, Mohsin Hafeez, Jan Lundqvist, J.V. Meenakshi, Lyla Mehta, Dawit Mekonnen, Franz Rojas-Ortuste, Aliya Tankibayeva, Stefan Uhlenbrook 7. **Crop Diversity, its Conservation and Use for Better Food Systems. The Crop Trust Perspective** Stefan Schmitz, Rodrigo Barrios, Hannes Dempewolf, Luigi Guarino, Charlotte Lusty, Janet Muir 8. **Climate Change and Food Systems** Alisher Mirzabaev, Lennart Olsson, Rachel Bezner Kerr, Prajal Pradhan, Marta Guadalupe Rivera Ferre, and Hermann Lotze-Campen 9. **Livestock and sustainable food systems: Status, trends, and priority actions** Mario Herrero, Daniel Mason-D'Croz, Philip K. Thornton, Jessica Fanzo, Jonathan Rushton, Cecile Godde, Alexandra Bellows, Adrian de Groot, Jeda Palmer, Jinfeng Chang, Hannah van Zanten, Barbara Wieland, Fabrice DeClerck, Stella Nordhagen, Margaret Gill 10. **The Vital Roles of Blue Foods in the Global Food System** Jim Leape, Fiorenza Micheli, Michelle Tigchelaar, Edward H. Allison, Xavier Basurto, Abigail Bennett, Simon R. Bush, Ling Cao, Beatrice Crona, Fabrice DeClerck, Jessica Fanzo, Jessica A. Gephart, Stefan Gelcich, Christopher D. Golden, Christina C. Hicks, Avinash Kishore, J. Zachary Koehn, David C. Little, Rosamond L. Naylor, Elizabeth R. Selig, Rebecca E. Short, U. Rashid Sumaila, Shakuntala H. Thilsted, Max Troell, Colette C.C. Wabnitz

Advance Equitable Livelihoods, Decent Work and Empowered Communities	• Decent Work and Living Incomes • More and Better Jobs for Youth • Making Food Systems Work for Women and Girls • Indigenous Rights and Traditional Knowledge	1. **Advance Equitable Livelihoods- A Paper on Action Track 4** Lynnette M. Neufeld, Jikun Huang, Ousmane Badiane, Patrick Caron, Lisa Sennerby Forsse 2. **A review of evidence on gender equality, women's empowerment, and food systems** Jemimah Njuki, Sarah Eissler, Hazel Malapit, Ruth Meinzen-Dick, Elizabeth Bryan, and Agnes Quisumbing 3. **Indigenous Peoples' Food Systems – Characterization, Concept and Application for the UN Food Systems Summit (Wiphala Paper)** 4. **Marginal areas and indigenous people – Priorities for research and action** Sayed Azam-Ali, Hayatullah Ahmadzai, Dhrupad Choudhury, Ee Von Goh, Ebrahim Jahanshiri, Tafadzwanashe Mabhaudhi, Alessandro Meschinelli, Albert Thembinkosi Modi, Nhamo Nhamo, Abidemi Olutayo 5. **The Future of Small Farms: Innovations for Inclusive Transformation** Xinshen Diao, Thomas Reardon, Adam Kennedy, Ruth S. DeFries, Jawoo Koo, Bart Minten, Hiroyuki Takeshima, and Philip Thornton
Build Resilience to Vulnerabilities, Shocks and Stresses	• Local Food Supply Chains • Climate Resilient Development Pathways • Humanitarian Development Peace Nexus • Safety Nets	1. **Building Resilience to Vulnerabilities, Shocks and Stresses- A Paper on Action Track 5** Thomas W. Hertel, Ismahane Elouafi, Frank Ewert and Morakot Tanticharoen 2. **Food Systems Innovation Hubs in Low-and-Middle-Income Countries** Kalpana Beesabathuni, Sufia Askari, Madhavika Bajoria, Martin Bloem, Breda Gavin-Smith, Hamid Hamirani, Klaus Kraemer, Priyanka Kumari, Srujith Lingala, Anne Milan, Puja Tshering, Kesso Gabrielle van Zutphen, Kris Woltering 3. **A Whole Earth Approach to Nature Positive Food: Biodiversity and Agriculture** Fabrice A.J. DeClerck, Izabella Koziell, Tim Benton, Lucas A. Garibaldi, Claire Kremen, Martine Maron, Cristina Rumbaitis Del Rio, Aman Sidhu, Jonathan Wirths, Michael Clark, Chris Dickens, Natalia Estrada Carmona, Alexander K. Fremier, Sarah K. Jones, Colin K. Khoury, Rattan Lal, Michael Obersteiner, Roseline Remans, Adrien Rusch, Lisa A. Schulte, Jeremy Simmonds, Lindsay C. Stringer, Christopher Weber and Leigh Winowieck 4. **Delivering climate change outcomes with agroecology in low- and middle-income countries: evidence and actions needed** Sieglinde Snapp, Yodit Kebede, Eva Wollenberg, Kyle M. Dittmer, Sarah Brickman, Cecelia Egler, Sadie Shelton 5. **Priorities for inclusive urban food system transformations i the Global South** Paule Moustier, Michelle Holdsworth, Dao The Anh, Pape Abdoulaye Seck, Henk Renting, Patrick Caron, Nicolas Bricas
		6. **Secondary Cities as Catalysts for Nutritious Diets in Low- And Middle-Income Countries** Kesso Gabrielle van Zutphen, Dominique Barjolle, Sophie van den Berg, Breda Gavin-Smith, Klaus Kraemer, Capucine Musard, Helen Prytherch, Johan Six, Simon Winter, Kris Woltering 7. **Addressing Food Crises in Violent Conflicts** Birgit Kemmerling, Conrad Schetter, Lars Wirkus 8. **COVID-19 and Food Systems: Rebuilding for Resilience** Patrick Webb, Derek J. Flynn, Niamh M. Kelly, Sandy M. Thomas, and Tim G. Benton on behalf of the Global Panel on Agriculture and Food Systems for Nutrition 9. **In the age of pandemics, connecting food systems and health: a Global One Health approach** Gebbiena M. Bron, J. Joukje Siebenga, Louise O. Fresco

Means of Implementation	• Finance Efforts • Government Efforts • True Value of Food • Science, targets • Data • Capacity Efforts	**1. Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit** Joachim von Braun, Kaosar Afsana, Louise O. Fresco and Mohamed Hassan **2. Achieving Zero Hunger by 2030 – A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals** Hugo Valin, Thomas Hertel, Benjamin Leon Bodirsky, Tomoko Hasegawa, Elke Stehfest **3. Ending Hunger by 2030 – policy actions and costs** Joachim von Braun, Bezawit Beyene Chichaibelu, Maximo Torero Cullen, David Laborde, Carin Smaller **4. Financing SGD2 and Ending Hunger** Eugenio Díaz-Bonilla **5. The True Cost and True Price of Food** Sheryl Hendriks, Adrian de Groot Ruiz, Mario Herrero Acosta, Hans Baumers, Pietro Galgani, Daniel Mason-D'Croz, Cecile Godde, Katharina Waha, Dimitra Kanidou, Joachim von Braun, Mauricio Benitez, Jennifer Blanke, Patrick Caron, Jessica Fanzo, Friederike Greb, Lawrence Haddad, Anna Herforth, Danie Jordaan, William Masters, Claudia Sadoff, Jean-François Soussana, Maria Cristina Tirado, Maximo Torero, Matthew Watkins **6. The Transition Steps Needed to Transform Our Food Systems** Patrick Webb, Derek J. Flynn, Niamh M. Kelly, and Sandy M. Thomas on behalf of the Global Panel on Agriculture and Food Systems for Nutrition **7. The Role of Science, Technology and Innovation for Transforming Food Systems Globally** Robin Fears, Claudia Canales **8. How could science–policy interfaces boost food system transformation?** Etienne Hainzelin, Patrick Caron, Frank Place, Arlène Alpha, Sandrine Dury, Ruben Echeverria, Amanda Harding **9. Food System Innovations and Digital Technologies to Foster Productivity Growth and Rural Transformation** Rui Benfica, Judith Chambers, Jawoo Koo, Alejandro Nin-Pratt, José Falck-Zepeda, Gert-Jan Stads, Channing Arndt **10. Leveraging data, models & farming innovation to prevent, prepare for & manage pest incursions: Delivering a pest risk service for low-income countries** Taylor, B; Tonnang, HEZ; Beale, T; Holland, W; Oronje, M; Abdel-Rahman, EM; Onyango, D., Finegold, C; Zhu, J; Pozzi, S, Murphy, ST

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Report (Draft)
prepared by the Scientific Group for the Food Systems Summit
August 2021

SCIENCE FOR TRANSFORMATION OF FOOD SYSTEMS: OPPORTUNITIES FOR THE UN FOOD SYSTEMS SUMMIT

by Joachim von Braun, Kaosar Afsana, Louise O. Fresco, Mohamed Hassan
with the Scientific Group for the UN Food Systems Summit

ABOUT THE AUTHORS

The authors are Chair and Vice-Chairs, respectively of the Scientific Group. They developed this paper in close collaboration with the Scientific Group of the UN Food Systems Summit, which has engaged extensively with science communities around the world including the partners and contributors of more than 40 reports and briefs prepared specifically for the Scientific Group's evidence-based contributions to the Summit. The authors thank the participants of Science Days for their thoughtful input and comments on the draft paper, as well as all others who shared comments and suggestions.

Joachim von Braun (Germany) Chair of the Scientific Group. Director of the Center for Development Research (ZEF), Bonn University, and Professor for economic and technological change. President of the Pontifical Academy of Sciences.

Kaosar Afsana (Bangladesh) Vice Chair of the Scientific Group. BRAC James P Grant School of Public Health, BRAC University, Dhaka .

Louise O. Fresco (Netherlands) Vice Chair of the Scientific Group. President of the Executive Board, Wageningen University & Research.

Mohamed Hassan (Sudan) Vice Chair of the Scientific Group. President of The World Academy of Sciences for the advancement of science in developing countries (TWAS).

TABLE OF CONTENTS

SUMMARY

Food systems at the global level and in many countries and regions are failing to end hunger, they do not provide adequate nutritious foods for healthy diets, they contribute to obesity and do not assure safety of foods. How we produce and consume food has profound implications for the health of people, animals, plants, and the planet itself. A change in world views in support of a range of actions is needed to re-orient food systems dynamics. A central element of such change is a much greater emphasis on science for innovation to transform food systems towards sustainability and equity.

In this paper, we focus on the key role of science and research, as they are essential for innovations that accelerate the transformation to healthier, more sustainable, equitable, and resilient food systems. The problems of food systems are to a significant extent due to long delays between scientific warnings and policy responses, innovation-stifling regulatory regimes, low levels of science investments, and a lack of effective communication by science communities themselves. Moreover, inclusive research in many fields of food systems offers opportunities, where local communities are co-creators in the research and development of innovations with scientists who are open to related collaboration.

Science offers many important contributions to achieve the Food Systems Summit goals based on the SDGs, of which we highlight two here: first, science generates the basic inputs for innovations, i.e. policy and institutional innovations (incl. social and business innovations) as well as technology-based innovations to catalyze, support, and accelerate food systems transformation; and second, science scrutinizes actions, i.e. assessing ambitions, targets and actions on pathways towards reaching them, for instance through quantitative analyses and food systems modeling.

We stress that policy innovations, institutional innovations, and technology innovations are closely connect-

ed and actually need to be pursued in an integrated approach. Science alone is not a panacea to cure the diseases of the food system, but without science the necessary complex innovations will not be forthcoming.

We note the need for systems innovations rather than only single-issue innovations, and call on the science communities to commit to enhanced collaboration among all relevant different disciplines of sciences for this purpose. This includes recognition of and cooperation with knowledge systems of Indigenous Peoples. Moreover, science is not naïve vis á vis power relations, and social sciences explicitly uncover them and must identify options for innovations that help to overcome adverse effects.

Drawing on a comprehensive food systems framework, actions for seven science-driven innovations are elaborated in this paper, each with some concrete examples:

1. Innovations to end hunger and increase the availability and affordability of healthy diets and nutritious foods: this bundle partly draws on the six science and innovation actions below.
2. Innovations to de-risk food systems and strengthen resilience, in particular for negative emission farming and drawing on both advanced science as well as traditional food system knowledge.
3. Innovations to overcome inefficient and unfair land, credit, labor, and natural resource use arrangements, and facilitate the inclusion, empowerment and rights of women and youth, and Indigenous Peoples.
4. Bio-science and digital innovations for improving people's health, enhancing systems' productivity, and restoring ecological well-being.
5. Innovations to keep – and where needed, regenerate – productive soils, water and landscapes, and protect diversity of the agricultural genetic base and biodiversity.
6. Innovations for sustainable fisheries, aquaculture, and protection of coastal areas and oceans.
7. Engineering and digital innovations for the efficiency and inclusiveness of food systems and the empowerment of youth and rural communities.

These innovations and their related goal-oriented actions do not exist in silos; rather, there are synergies and trade-offs between them that must be considered to maximize the system-wide effectiveness and efficiency of proposed innovations and actions while ensuring equity and sustainability.

Fundamental conditions essential to enable and leverage food systems transformation to achieve the objectives include peace and security, and related diplomatic and security policies guided by the humanitarian-peace-development nexus, the full inclusion of marginalized and vulnerable populations, gender equity, sound governance at all levels from the community to local, national and international, and supportive global and national policies for public goods, such as climate policies and trade regimes.

Food systems transformations require private and public investments at scale, which means that there is an important role for innovation in financing. As a key food systems science policy target, we propose that governments allocate at least 1% of their food systems-related GDP to food systems science and innovation, with the perspective of exceeding that target. Least developed countries (LDCs) should be assisted in reaching this target quickly.

Investments in capacity for science and innovation need to expand, with more attention to strengthening local research capacities, developing more inclusive, transparent, and equitable science partnerships, promoting international research cooperation and addressing intellectual property rights issues where they hinder innovations that can serve food and nutrition security, food safety, and sustainability goals.

Food systems science and food systems policy need a stronger framework for constructive and evidence-based interaction for moving ahead, not only for the Food Systems Summit 2021 but for its follow-up and in the long term. In contrast to the other subjects of global concern that were agreed upon at the Earth Summit in Rio in 1992, agriculture, food, and nutrition do not have an international agreement or convention to consolidate actions as for climate, biodiversity and desertification. The time has come to consider such a set of agreements and mechanisms. The UNFSS may wish to consider exploring a pathway towards a treaty on food systems. This should include innovation and strengthening the science-policy interfaces at the local, national and international levels where these interfaces are connected and can be served with strong, trusted, and independent voices for science-informed and evidence-based food systems actions. We call upon governments and UN agencies to initiate a process to explore options – existing as well as new – for a strengthened global science-policy interface for a sustainable food system. As such, this could be a concrete outcome of the UNFSS.

1. OBJECTIVES OF THE PAPER

Science offers many important contributions to the Food Systems Summit, two of which we highlight here. First, science has an intrinsic role in generating new insights and the basis for new technologies and policy and institutional innovations (incl. social and business innovations). These are critical to catalyze, support, and accelerate food systems transformation to achieve the Food Systems Summit goals based on the SDGs. Second, science serves the Food Systems Summit's policy-makers to identify ambitious targets and actions for pathways towards reaching them, for instance by quantitative and qualitative analyses and food systems modeling. This paper aims to address both of these contributions of science.

We note that science is not a panacea for the necessary food systems innovations towards a sustainable system. Like other actions, science can even have negative external effects, to be prevented by ethics and public policy. Nonetheless, without accelerated interdisciplinary food systems science, the necessary innovations for a sustainable food system will not be achieved. Science and innovation are critical for achieving food systems that serve people and the planet.

The Food Systems Summit is the opportunity to address and resolve food system problems and failures. The aim of the Food Systems Summit is to help countries and stakeholders to maximize the co-benefits of a food systems approach across the entire 2030 SDG Agenda and address the challenges of climate change, soil degradation, and biodiversity loss. Action agendas defined in the Summit processes need to be evidence based.

It is not the purpose of this paper to develop an action agenda for the Summit, but rather to highlight the critical roles of science in a transformative agenda. This paper draws on the wealth of information generated by food systems-related science communities, including new syntheses by the Scientific Group and its research partners and many others (see references in the annex and end notes). In particular, we draw attention to the comprehensive contribution to knowledge about sustainable food systems by Indigenous Peoples[1] and the opportunities of mutual learning between traditional- and experience-based knowledge and science for innovation.

2. FRAMING THE FOOD SYSTEMS CONTEXT AND CONCEPTS

Food systems at the global level and in many countries and regions are failing to end hunger, provide adequate nutritious foods for healthy diets, or deliver safe foods. Between 720 million and 811 million people face hunger and are undernourished – that is every tenth person – 150 million children under five years of age are stunted (short for their age), and two billion people are overweight or obese. These numbers have been high and/or growing for a number of years now, and with COVID-19 disproportionately impacting poor and food-insecure populations, they are continuing to rise with an estimated 118 million more people facing hunger in 2020 than in 2019.[2,3] About 600 million people fall ill each year due to the consumption of contaminated or unsafe foods.[4] **We are losing ground on the progress that we have already made**, and we face the prospect of severely compromising the achievement of the SDGs and the 2030 Agenda.

Besides escalating hunger and all forms of malnutrition (micronutrient deficiencies, underweight, overweight/obesity and related NCDs), poverty and inequalities between and within countries are widespread and becoming entrenched. For many people, engaging in activities in the food system would seem to offer the most viable opportunities to escape poverty, yet they are being left out of earning their fair share of the benefits from engaging in food systems, and are condemned to jobs that do not provide livable wages and decent working conditions and livelihoods. Fundamental human rights to food, health, safe water and sanitation, and education continue to be violated. Ending poverty and gross inequalities remains essential for achieving the SDGs.

Food systems relate to the three basic dimensions of sustainability: social, economic, and environmental.[5] Many food systems are based on production and distribution systems that are simply not sustainable. Scientific assessments indicate that many aspects of current food production systems drive the degradation of land and soil, water, and climate, as well as biodiversity loss.[6,7] Climate change is increasingly adversely impacting food security. The global food system emits about 30% of global greenhouse gases, contributes to 80% of tropical deforestation, and is a main driver of soil degradation[8] and desertification, water scarcity, and biodiversity decline. Climate change along with soil and environmental degradation are partly caused by – and have negative impacts – on the food system. It is very clear that **how we produce and consume food has profound implications for the health of people, animals, plants, and the planet itself**.[9]

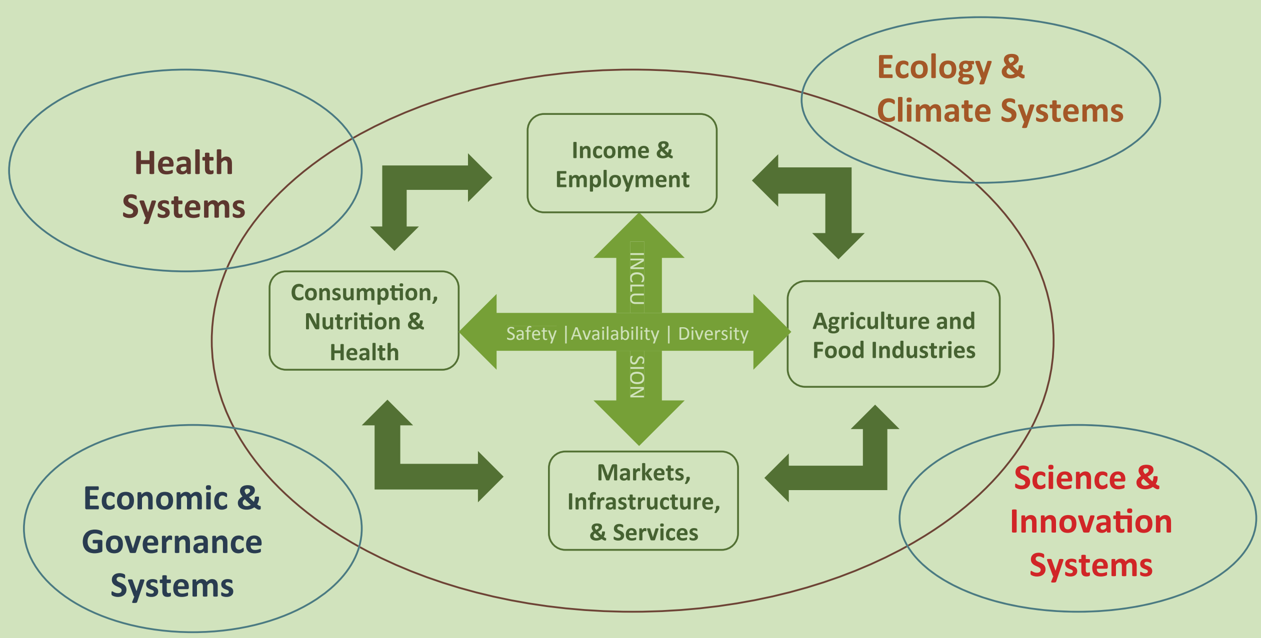
The Food Systems Summit is taking place in the midst of the COVID-19 pandemic, which has revealed the close intertwining of food, ecological, and health systems.[10] The pandemic is having a significant impact on the global commodity markets and trading systems, economic growth, incomes, and poverty levels, with disproportionate burdens on vulnerable communities in both urban[11] and rural areas. This is likely to worsen inequalities and undernutrition, including child undernutrition, which can have life-long consequences. Modeling projects that COVID-19 could result in an additional 9.3 million children wasted (low weight for height) and 2.6 million children stunted (low height for age) by 2022.[12] COVID-19 further increases food insecurity and poverty, which may become much more serious if comprehensive policy responses – especially equal global vaccination coverage – are not implemented in a timely, and evidence-based manner.[13]

Box: Conceptualizing Food Systems[14]

"Food systems embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products that originate from agriculture (including livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded…". "A sustainable food system is one that contributes to food security and nutrition for all in such a way that the economic, social, cultural, and environmental bases to generate food security and nutrition for future generations are safeguarded". Its sustainability is not to be realized internally and in isolation with the food systems serving humanity, but depends upon its relationships with nature and ecological systems of which humankind is a part, with its destructive impacts that need to be overcome by food systems transformations.

Food systems are connected to other systems such as health, ecology and climate, economy and governance, and science and innovation (see Figure 1). A conceptual framework of food and nutrition systems should capture the delivery of health and well-being while being embedded in the transformation towards a sustainable circular bio-economy. Science and innovation impact the functioning of the system as a whole and within its building blocks and the interconnections among them.

Figure 1 Food systems conceptual framework



An integrated approach with which Indigenous Peoples look at food systems and the elements that compose them, weaves the different elements into systemic practices, generate foods while preserving biodiversity.[1]

Science needs to explore the root causes of emerging zoonotic diseases, and closely engage with policy innovations, including related to land use and animal production. Going forward, it is abundantly clear that **more attention will need to be paid to how to make food systems more resilient to health shocks and pandemics, associated economic shocks and slowdowns, and violent conflicts and other crises**, just as more attention is being now paid to how to make food systems more resilient to extreme weather events and other stressors induced by the changing climate.[15] This will require integrated approaches that create greater synergy across government efforts to deal with health and other social services as well as food system failures in rural areas and other marginal communities.[16]

The changing state of the art of science and innovation and the important lessons that they offer for food systems transformation need to be recognized. As noted earlier, science has at least two important roles for food systems: first, science generates new breakthroughs that can become innovations in food systems (e.g. genomics, plant nutrition, animal production and health, bio-sciences, earth sciences, social sciences, remote sensing, AI and robotics, digitization, remote sensing, big data, health and nutrition science, behavioral research, etc.); and second, science helps to inform and shape decisions, investments, policies and institutions and it can also be involved in the design, implementation and monitoring of action to learn and draw lessons for impact at scale.[17] This also includes science that focuses on knowledge gaps, risks, uncertainties, and controversies. Many approaches from discovery research to implementation research and including both primary research and modeling techniques can contribute valuable evidence.

3. OPPORTUNITIES FOR SCIENCE AND INNOVATION TO ACHIEVE THE FOOD SYSTEMS SUMMIT GOALS

Science and research are fundamental drivers of innovation. All three – science, research, and innovation – are essential to accelerate the transformation to healthier, more sustainable, equitable, and resilient food systems.[18] To enable the full inclusion of poor and marginalized populations – including smallholder communities[19] – in the process of and benefit from food systems transformation, investments in technology-based innovations must be accompanied by institutional innovations (incl. social, business and policy innovations), underpinned by science: basic sciences and applied sciences, natural sciences and social sciences. The Scientific Group underlines not only its respect for Indigenous Peoples[1] knowledge systems but recommends investing more in programs exploring mutual learning and innovation across traditional and modern knowledge and science systems considering both on an equal footing. This may include documenting this knowledge and jointly studying it scientifically.

The Scientific Group highlights the **need for systems innovations rather than only single-issue innovations**, and calls for enhanced collaboration between and among different disciplines of sciences for this purpose. The Scientific Group suggests a focus on seven science-driven innovations to catalyze, support, and accelerate food systems transformation to achieve the Food Systems Summit goals and thereby the SDGs and SDG2 in particular. These innovations emerge from our conceptual framework and the building blocks and linkages therein (see Box). We hasten to emphasize that technology-based innovations and policy and institutional innovations are in synergy among each other: in other words, many technology-based innovations need policy and institutional innovations to fully realize their potential (for instance, innovative financing mechanisms), and similarly many policy and institutional innovations need technology-based innovations to be properly implemented and monitored (for instance, information systems). Further, in many instances, food systems innovations must be place-based, adapted to the local contexts and capacities. We provide **examples of science-based innovations in the seven action areas below, identifiable in cursive format**. Alignment of technological change with sustainability concerns certainly requires attention and joint engagement by researchers from all areas of the food systems-related sciences (including social sciences) guiding innovation arrangements.

3.1. Innovations to end hunger and increase the availability and affordability of healthy diets and nutritious foods.

More than 3 billion people cannot afford healthy diets, and more than 1.5 billion people cannot even afford a diet that only meets the required levels of essential nutrients.[2,20] The contribution of science and innovation here relates to identifying optimal context-specific investment opportunities and their implementation. Broadly speaking, the investment opportunities include productivity enhancement, people's skills and empowerment, agricultural research, social protection, nutrition programs, etc.[21] Policy innovations are needed to repurpose subsidies towards related supportive investments that facilitate a sustainable food system.[22]

Food is undervalued. The value of food from a cultural, social and economic perspective needs revisiting.

An important role of science here is also to identify their indirect effects, while efforts must be made to embrace the true value of food.[23] External costs associated with climate change,[24] biodiversity loss, and adverse health effects need to be considered. True cost accounting approaches are to be pursued in the whole food system, and related capacities built up in the corporate and public sectors. Capacities for internalizing such externalities are limited.[1] Cautious approaches are warranted to develop price and non-price instruments, including regulatory-based instruments, to help deal with such externalities. Fostering positive externalities of the food systems such as by carbon farming and biodiversity-enhancing land use should be considered and tested where justified.[25] Nonetheless, if food prices were to reflect true costs, food healthy diets may become unaffordable for low-income consumers, and social safety nets would need to be put in place.

Healthy diet concepts benefit from a stronger science basis.[26] Measures that incentivize the production and market supply of fruits and vegetables and related innovations enhance consumption and can increase the income of small holders.[27] However, rising incomes of consumers do not automatically lead to the increasing consumption of healthy diets: even when accessibility and affordability are not constraints, the consumption of healthy diets is not assured as people may still not change their consumption behavior. Approaches to create demand for healthy diets and nutrition must be explored. At the same time, we have to be careful not to put all of the blame for poor nutrition on consumer behavior.[28] Considerably more science is needed to understand the drivers in the processing, marketing and food environments. Science-intensive and promising opportunities such as scaling up sustainable cold chain technology to make perishable foods (especially vegetables and fruits; potatoes) more available and affordable[29] and at the same time reducing food loss and waste must be pursued, along with complementary investments in infrastructure to reduce transportation and other related costs and thereby reduce food prices.[30]

Nutrition science – like all science – is conflicted and much of our real understanding of these nutrition issues is only starting to emerge. More research is needed to identify the most adequate healthy diets and their affordability and environmental sustainability across different contexts.[31] Dietary targets elaborated by the World Health Organization (WHO) – such as those related to adequate fruits and vegetable consumption, sweeteners, etc. –should be considered accordingly. A potentially very significant contribution to deepened insights in health aspects of diets is the "Periodic Table of Food Initiative (PTFI)", a global effort to create a public database of the bio-chemical composition and function of the food that we eat using the latest mass spectrometry technologies and bioinformatics.[32] If further combined with micro-biome science of human nutrition,[33] the perspectives on healthy diets may further be shifting and related health and information actions can become more concrete, including for the prevention of obesity.

We need to better understand how to design and implement policies that enable healthy food environments, especially for children, such as through taxes on foods whose excessive consumption should be avoided, limitations on advertisements of unhealthy foods, information by educational food labeling, prohibition of trans-fats, and regulation of the use of high-fructose corn syrup. Sound implementation of nutrition education is likewise required. Information about health properties from industrial fortification and biofortification of certain foods should also be considered.[34,22] Research on the costs of action versus no-action regarding the key drivers of diets and food systems change and the impact of these changes is required for effective decision-making.

3.2. Innovations to de-risk food systems and strengthen resilience, in particular for negative emission farming and drawing on both advanced science as well as traditional food system knowledge.[35]

As food systems become more global, dynamic, and complex, they also become more vulnerable to new, challenging, and systemic risks, as evidenced by the food price crisis in 2008, the ongoing COVID-19 pandemic,[36] and in armed conflicts.[37] The implementation experiences of triple nexus approaches of the humanitarian-peace-development nexus should be accompanied with evidence-seeking social science.[38] Science-based responses to catastrophes require preparedness. The capacity to understand, monitor, an-

1 It should be noted that lower food prices – if they come about in the short term – might have adverse income effects for producers, and discourage them from investing to protect the ecosystem, especially if ecosystem services related to food systems are not incentivized, but more relevant is the avoidance of extreme price volatility, because that reduces incentives to invest and hurts farm households.

alyze, and communicate vulnerabilities, crises, and risks must be strengthened.[39] Opportunities to expand and improve food security forecasting and monitoring with web-based approaches must be seized. Local meteorological capacities must be expanded as accurate weather forecasting is of critical importance to farming communities. De-risking food systems by solar powered small-scale irrigation and affordable smart phones with location-specific soil and weather data are concrete innovations that can be scaled.

Food prices currently show fast upward movements, and increased volatility. Such tendencies on top of the income losses due to COVID-19 add to food security dangers for the poor. Care must be taken to avoid erratic policies, especially trade policies. While strategic food reserves can play a role in ensuring resilience to supply shocks, open rule-based trade – both international and interregional – can provide a more economical option for dealing with localized extreme weather events. Ensuring free and rule-based open food trade will require a rejuvenation of multilateral trade negotiations. In addition, to avoid panic-induced world price spikes, transparent information on production, stocks and government interventions around the world are critical and must be made widely available. The Agricultural Market Information System (AMIS) is an important step in this direction.[40]

Climate change is the defining issue of our time.[41] Agriculture as well as forestry and related land use change are the single largest drivers of multiple environmental pressures, and major contributors to greenhouse gas emissions. While they are part of the overall climate change problems, they must also be part of the solutions. Good resource management practices for soil and water that contribute to promoting sustainable food systems must be rewarded, with payments for ecosystem services as an option.[42] In some countries, there is a need to reduce the over-use of chemical fertilizers that leads to a large environmental pollution and climate change. Boosting nature-based solutions[43] and nature-positive production calls for transforming soil management, farm input use, agronomy,[44] and livestock and aquatic food systems in ways to sustainably boost production to meet current and future food demands, protecting and using biodiversity through biophysical and ecological practices,[45] rapid reduction of the use of pesticides in intensive crop production, of antibiotics and steroids, and protecting the agriculture- and forest-related genetic base.[46] Of critical importance in this context is the rapid reduction of the use of antibiotics and steroids in livestock and aquatic food production systems. Greater emphasis must also be given to the development of green technologies that deploy ecologically suitable trees and indigenous perennial species to boost nature-positive production, and the reduction of large monocultures.[47] Similarly, organic fertilizers and bio-stimulants from land and marine sources that can replace chemical fertilizers in promoting soil plant growth and increasing yields can be further explored.[48] Novel insurance products and efficient social protection programs that include job creation and a variety of nutrition programs including school-feeding programs strengthen resilience.[49]

Future scientific and technological developments can increase the portfolio of bioproducts developed from local biodiversity, in keeping with a circular bio-economy approach.[50] Accelerating the reduction of food waste and loss calls for developing food processing, refrigeration, storage and warehouse technologies.[51] It also calls for modifying consumption behaviors, lifestyle choices, and the perverse incentive to buy much more than needed. Moving quickly towards climate-positive and climate-resilient food systems should employ carbon pricing at appropriately high levels and incentives for technologies that facilitate adaptation and mitigation.[22] Initiatives for carbon farming (growing carbon in soil and trees as a tradable commodity) and related payment schemes should be explored. Climate finance for adaptation has important ecological opportunities in the food system and is also pro-poor. It only currently accounts for a very small proportion of climate finance, which needs to increase.[52]

Food systems need to become more prepared for and resilient not only to extreme weather events and climate shocks, but to market and inflationary shocks, health shocks, natural disaster shocks, political/governance shocks, cyber shocks, and other emerging shocks. The characteristics, scale and impact of risks continue to evolve,[53] and food-related crises are rising in likelihood and severity. Science also has a growing role in developing a common language to converge multiple knowledge systems and shared goals under emerging risks and uncertainties and how to prepare for and manage them.

Rigorous implementation research is needed to strengthen the fit-to-context design and delivery of such programs and thereby strengthen the resilience of chronically vulnerable communities and their food systems.

3.3. Innovations to overcome inefficient and unfair land, credit, labor, and natural resource use arrangements, and facilitate the inclusion, empowerment and rights of women and youth and Indigenous Peoples.[22]

Poverty and hunger are interlinked and reducing extreme poverty directly impacts the elimination of hunger and malnutrition. Among the effective ways to sustainably eradicate poverty and inequality is boosting the opportunities and capacities of the poor and those living in situations of vulnerability, through ensuring more equitable access to resources, i.e. to natural resources and economic assets. Providing and protecting land rights of smallholders – especially female smallholders, and Indigenous Peoples – is critical in this context, as is overcoming exploitative share tenancy. Inclusive approaches are more possible, affordable and controllable through block chain ledgers of land ownership and credit.

Ensuring decent work is a key area and calls for regulation and value chain transparency. The potential for significantly expanding green jobs within food systems must be vigorously pursued. Pro-poor asset sharing investments and programs that empower poor people to build their asset base offer promise. Nonetheless, eliminating poverty alone does not make healthy diets affordable for all. Changing food systems need to ensure that people with low incomes can access a healthy diet by enabling them to earn living wages and have access to social safety nets.

The roles of **women** are very important for productive, healthy and sustainable food systems.[44] Many food systems are unequal or breed inequalities through land and other asset ownership and market power relationships, whereby power imbalances are a common phenomenon. Besides gender inequalities, overall inequalities across classes, regions, rural-urban contexts, and social groups also influence whether food systems will transform to be healthier, more sustainable, and equitable. Women's voices in policy-making – being cognizant of the needs and wants of women and societal norms and issues – is critical.

The situation of the **youth** as well as the elderly deserves particular attention. Key innovations include policies to transform land tenure in equitable ways, provide more and better education investments that enable and empower youth and women and allow them unfettered access to knowledge and information, facilitate job training and education programs, provide affordable financial services, and include youth more fully and meaningfully in policy-making processes. Vocational training with multi-facetted curricula relevant for rural economic space and food systems are to be scaled up. Youth have the right and responsibility to learn about food systems dynamics and to be fully engaged in opportunities to transform the food systems that they will inherit. The inclusive transformation of smallholder farming will be imperative for youth. Smallholders are not a homogenous group, and transformation of the small farm economy around the world will call for different policies to address the heterogeneity of smallholders.

3.4. Bio-science and related digital innovations for people's health, food systems' productivity,[54] and ecological well-being.[41,55]

Specific science opportunities for innovations here include genetic engineering, genome editing, alternative protein (including more plant-based and insect-derived protein) sources[56] and essential micronutrient sources, cell factories, microbiome and soil and plant health technologies, plant nutrition technologies,[57] animal production and health technologies. These advances in science and technology have great potential to meet food system challenges such as restoring soil health and functionality,[58] improving the resource efficiency of cropping systems[59], breeding orphan and underserved crops,[60] and re-carbonization of the terrestrial biosphere. Modern plant breeding techniques that allow plants to capture nitrogen from the air reduce the need for fertilizers and improve nutritional qualities.

However, it must not be neglected that there are potential risks associated with science-based innovations that need to be considered within the science systems and with societal dialogues through transparency, ethical standards and reviews, biosafety measures, and – where needed – with regulatory policies. Adopting the One Health approach, i.e. the health of soil, plants, animals, people, ecosystems and planetary processes, being one and indivisible, would make an important contribution.[61]

Translating bio-science innovations into reality does not happen automatically: property rights, skills, and data are key for the translation and management of scientific innovations in practice.[62] However, bio-sciences increasingly benefit from digital innovations and artificial intelligence.[63] Nonetheless, these technologies sometimes run the risk of exclusion through the creation of monopolies that need to be prevented by anti-trust regulations. Hence, innovations in governance structures are needed to ensure that access to bio-science and digital technologies is not hindered. Furthermore, developing these bio-science and digital innovations and ensuring that they – especially the potentially controversial technologies – contribute to sustainability is not sufficient; rather, it will be important to adapt them to local conditions, make them accessible and affordable to farmers, especially smallholders, and use them to enhance local and traditional knowledge. It will also be important to have open information sharing so that users are aware of the opportunities, costs and benefits of new innovations and able to better use the available technology and implement innovations.[64] To ensure that poor communities are not left behind, governments of countries in the global South need to invest in the creation of capacities and expertise to develop and utilize bio-sciences and digital technologies and receive support for that from development partners. It is important that Indigenous Peoples and local people in general receive the benefits of their interactions and information sharing with scientists that result in innovations.

3.5. Innovations to keep – and where needed, regenerate – productive soils, land and water, and protect the agricultural genetic base and biodiversity.

One-third of global land area is degraded.[65] Soil degradation is being exacerbated by climate change along with land mis-use and soil mismanagement.[66] Water is becoming increasingly scarce and polluted.[67] Ecosystems services of land, forests, and water cycles are being undermined.[68] Technology-based innovations are needed to support sustainable soil, agricultural, and water management, protect natural resources from degradation and restore degraded resources, and maintain and even increase biodiversity in agricultural settings.[69,70] This underlines the need to advance knowledge in plant genetic diversity and microbial diversity, taking local climate variability into account.[71] Harnessing soil microbes to add to depleted soils to improve structure, carbon capture and yields are promising innovation opportunities. The use of modern hand-held digital devices for in-field measurement of soil carbon and remote sensing measurement of soil carbon can become significant opportunities for both climate policy and productive plant nutrient management. These examples highlight the interconnectedness of technological and policy innovations, because the technologies can facilitate the increased feasibility of payments for ecosystems services.

Similarly, agro-ecology and other regenerative practices for resilient landscapes at scale promise opportunities. They need long-term accompanying science. An integrated approach for sustainable soil management should be considered and incentivized. Locally-adapted sustainable intensification of existing agricultural systems is also needed.[72]

Primary forests are over-exploited, including due to the non-sustainable expansion of agriculture. Innovations in agroforestry with trees and bushes and in landscape contexts can contribute to large-scale productive land use combined with ecological and climate-positive ecosystems services.[73] Wild foods (e.g. berries and fruits) are important for food security and nutrition for both smallholder farmers and Indigenous Peoples. Traditional food and forest systems – including Indigenous Peoples' food systems – need to be better understood and protected, when designing policies.[75]

3.6. Innovations for sustainable fisheries, aquaculture, and protection of coastal areas and oceans.

There is a tendency to think of food systems as terrestrial systems only. Given the tremendous current and future potential of wild and farmed seafood and seaweed to help assure healthy diets, it is critical to broaden the understanding of food systems to more fully include the aquatic food systems.[76]

Institutional innovations are needed to overcome the mis-use of oceans as commons. We are approaching tipping points in harvesting from nature, and unless we stop treating the oceans as commons that can be exploited for perpetuity, we will accelerate species extinction among other irreversible changes. Ecological science perspectives and global cooperation and institutions are needed to bring the harvesting of oceans to sustainable levels and protect biodiversity.

Science-based innovations for sustainable aquatic foods that protect, and harness oceans and coastal areas can play a growing role in reducing hunger and malnutrition and building healthy, nature-positive and resilient food systems.[77] Innovations must support aquatic foods "to increase nutritional diversity, reduce waste, address environmental change and management failures, improve livelihoods of fishing and coastal communities, and capitalize on opportunities to sequester carbon in the marine environment".[78] Of critical importance are innovations in fish feeding systems: using insect rearing and oil rich modified legumes as fish feed in improved aquaculture to avoid depletion of oceans can become options. Enhancing the use of organisms of lower trophic levels for human consumption, e.g. micro-algae and seaweed can also evolve as foods.

3.7. Engineering and digital innovations for efficiency and inclusiveness of food systems and empowerment of the youth and rural communities.

Digital innovations and engineering that hold much promise to make food systems more efficient, productive, and sustainable are touching on all components of food systems. Examples include artificial intelligence, big data analysis, remote sensing, and robotics,[79] mechanization, sub-surface drip irrigation with conservation agriculture, precision agriculture, vertical farming, indoor farming, and digitized food processing.[80] The use of sensors to monitor origin and quality of products and ingredients all along the food chains to reduce losses, guarantee safety and reduce unnecessary "in-transparencies".

Some of the ways in which digital innovations can be put to work to optimize agricultural production processes include using drones and advanced analysis of image data to identify pests and diseases in real time. With improved access to biotic (pests and diseases) or physical (meteorological, SAT early warning systems) information and remote sensing, producers can use their mobile phones to strengthen their agricultural practices and make better use of inputs and resources.

Digitization in the food system is not necessarily enhancing equity, and it may even benefit large-scale farming and processing at the expense of smallholder farming. Thus, appropriate governance structures are needed to ensure that access to digital technologies is not hindered and that data collected from smallholders are appropriately protected so that smallholders are not "data-exploited". Inequitable access to digital technologies could significantly impede the transition to equitable food systems. Easing information access for women is particularly important. Strengthening the e-commerce ecosystem could transform rural livelihoods, providing platforms to reach the last-mile households and better connect them to the wider economy.

The growing role of digital innovations in science and technology processes that serve bio-chemical sciences and engineering of relevance for food systems is also noteworthy. It is of note that digitization itself facilitates decentralized organization of science and research producing technological, policy and institutional innovations that are context-specific, and thereby it offers extraordinary new opportunities to re-organize how science is undertaken, delivered, and used in participatory ways.

Further development to make digital technologies affordable and accessible for small- and medium-sized farmers is essential to avoid even further reducing their competitiveness.[81] In this context, revisiting and reinvigorating agricultural extension services with digital options is called for. Attention to employment effects is also called for, as well as attention to ethical considerations of data use and data ownership. Investments are also needed to scale up universal access to digital technologies and key infrastructure, in particular access to rural electrification, wherever possible based on renewable energy sources.

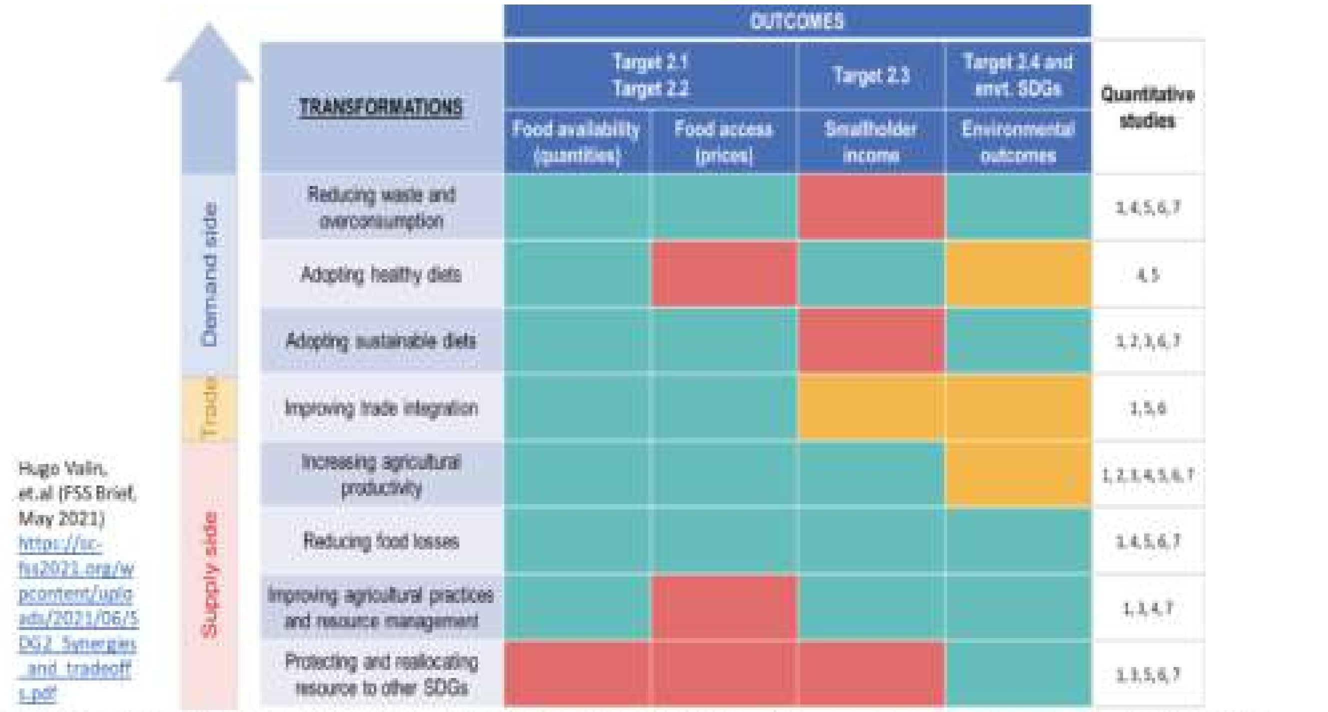
4. MODELING SYNERGIES AND TRADE-OFFS BETWEEN ACTIONS IN FOOD SYSTEMS

The sets of innovations and actions mentioned above are connected, and there are synergies and trade-offs among them. Understanding these synergies and trade-offs is critical in maximizing the effectiveness of innovations and actions. A convincing game-changing action in one food systems domain may cause adverse effects in another domain. For example, a fertilizer subsidy that increases income and reduces hunger may have an adverse environmental effect if this leads to excessive nitrogen use. To avoid such unintended consequences, food systems modeling is essential.

Furthermore, food systems do not operate in isolation. Innovations go beyond food systems and are connected to transformations in health systems ("One Health"), energy and environment systems (climate), economic systems (trade), and evolving science and knowledge systems. Strengthening the interactions among scientists specializing in food systems, health, climate, and energy will make it possible to generate the required expertise. Furthermore, researchers and users of research need to work together to increase the chances of achieving food systems-related SDGs. Supporting local innovations, creating knowledge, participatory science, and living labs should be explored at scale.

A recent review of the advanced quantitative global modeling found **strong synergies between SDG2 and other related SDGs**. These synergies and trade-offs are illustrated in Figure 2. In particular, SDG1 (no poverty) is central for food security and can unlock many additional benefits across the SDGs. SDG2 is closely integrated with SDG3 (good health and well-being) due to the close link between malnutrition and maternal and child health, as well as deaths associated with poor diet. Other socioeconomic SDGs — including SDG4 (education), SDG5 (gender equality), SDG8 (decent work and economic growth), SDG10 (reduced inequality), SDG11 (sustainable cities and communities), SDG16 (peace, justice and strong institutions),

Figure 2 Key transformations implemented in global analyses and their typical impact for relevant indicators (Valin et al., 2021)



Key transformations implemented in global analyses and their typical impact for relevant indicators: green = positive impact, red = negative impact, orange = ambiguous impact. Study references: 1 - Vuuren et al. (2015); 2 - Erb et al. (2016); 3 - Obersteiner et al. (2016); 4 - Willet et al. (2019) / Springmann et al. (2018); 5 – Deppermann et al. (2019); 6 - Leclere et al. (2020); 7 - Gerten et al. (2020)

and SDG17 (partnership) — are key enablers for SDG2. These potential synergies merit greater attention for accelerating food systems transformation.

The importance of trade-offs must also be recognized. Agricultural production substantially contributes to global warming, nutrient pollution, degradation of water quantity and quality, biodiversity loss, and soil degradation. Climate action (SDG13) requires curtailing greenhouse gas-intensive products (meat, dairy, rice). Achieving biodiversity on land (SDG15) requires limiting deforestation associated with agriculture expansion and establishing new conservation areas. Achieving environmental water flows (SDG6) requires reducing water withdrawal for irrigation. Quantitative assessments show more efficient production systems and technologies and pricing of externalities. Additionally, integrated resource management can mitigate some of these trade-offs, although they are unlikely to succeed in addressing them altogether.

Forward-looking analyses indicate that to achieve the SDG2 targets and other goals, deeper transformation of food systems at the global level will be required, combining supply- and demand-side measures. Such transformation entails new supply-side investments, effective trade and markets, and modified consumer behavior, with a fast transition towards more sustainable and healthy diets and sharp reductions in food loss and food waste. SDG12 (responsible production and consumption) is a key goal for the successful transformation of global food systems to achieve SDG2.

With an integrated modeling framework – illustrated in Figure 3 – Laborde and Torero (2021) model six individual interventions similar to those presented in Figure 2 with respect to their impact on the food systems, the prevalence of undernutrition, ecological effects in terms of GHG emissions, land and energy use, and the use of chemical inputs. Given the synergies and complementarities between these scenarios, the authors assess them as a package. The sensitivity to the results is also assessed under different governance principles, such as land use policies.[2]

The scenarios are listed in Table 1 and organized around three main pillars: achievement of a more efficient and inclusive system, allowing consumers and

2 Other aspects of the global food systems, like trade policies, are also analyzed to see how they interact with the main interventions.

Figure 3 An integrated modeling framework: The MIRAGRODEP CGE (source: Laborde and Torero, 2021)

Table 1 Scenario definitions (source: Laborde and Torero, 2021)

Escenarios	Title	Description
More Justice	#1 Social safety net: healthy diets for everyone	Provide food stamps (income transfer that should be spent on food products) to eliminate the "poverty gap" between the per capita income of each household and the affordability of healthy diets cost line. The cost is initial calibrated on SOFI 2019 and updated based on model dynamics.
More Justice	#2 School Feeding Program	All kids between 6 and 11 years old have access to school feeding programs 200 days a year. Daily per capita ration includes 320 grams of fruits, 102 grams of grains, 51 grams of animal proteins (meat, fish, eggs), 480 grams of milk, and 100 grams of vegetables.
Better Choices	#3 Farm Subsidy Repurposing	All farm subsidies (outputs, inputs, others) are redistributed in the form a a subsidy to farmer revenue. The rate of support is computed endogenous by the model to maintain farm subsidy budget constant, but a sectoral bias is introduced. Nutrious and low-emissions products are subsidised at twice the average rate, while products with low nutrition value and high emissions are subsidised at half the average rate.
Better Choices	#4 Consumer's incentive reform	Taxation of red meat products in High Income and Middle Income countries. The level of tax is computed by the model to obtain a reduction of consumption of 15 percent in HIC (and UMIC in Europe), and 7.5 percent in UMIC (exc. Africa). The group of countries have been constructed by computing an index of "excess" consumption by comparing average daily intake with a sustaibale and healthy diet reference (i.e. Flexitarian diet in this case, but alternative diets give the same ranking of countries)
More Efficiency	#5 Innovation, Technology and Knowledge for Farmers	This package of interventions is aimed at increasing farm level productivity, while reducing environmental footprints. It has three components
		Increased/or improved **Irrigation** systems. % of each country cropland benefits from new investments by 2030. For regions with high rate of irrigated land (all Asian regions), we consider only an upgrade of existing materials, leading to no change in yield but a reduction in water inefficiency. For other regions, we consider an increase of water use (for irrigation, but with an improved average efficiency) but also a yield increase
		Increased **livestock** genetics and better practices for higher productivity (2%)and lower emissions per unit of output. % of the the herd of each country is improved by 2030.
		Extension services and farmer **training** to increase all farm productivity (total factor productivity, TFP). % of farmers in each country are covered. TFP is increased. In addition, carbon sequestration in soil is increased.
More Efficiency	#6 Reducing Food Waste and Loss	Reduction of 25% in all countries of food waste and food losses, including for left-on-the field
Combined actions	All except Safety Nets	Include actions 2 to 6. Since the Safety Net is computed to provide enough income to everyone to be able to afford healthy diets, it is important to consolidate all the other actions before this one.
Combined actions	All including Safety Nets	All actions, 1 to 6. While this package will take care of all vulnerable people, showing the consolidated impact on environmental and economic indicators is important (trade-off lens)
Combined actions	Everything with land use regulation	In this consolidated scenario, we do not allow for land use change (fixed amount of agricultural land) by considering a stronger land governance.

producers to make better choices. Only preliminary findings from Laborde and Torero (2021) are summarized here. The results of the different scenarios are consistent with the baseline of The State of Food Security and Nutrition in the World 2020, namely that in 2019 there were 690 million undernourished people in the world and healthy diets were unaffordable for almost 3 billion people.

The finding confirms that ending chronic hunger at a 5% level is feasible by 2030 with the appropriate balance of interventions. While no intervention alone could solve the problem, Figure 4 shows that key interventions to increase the efficiency of food systems — through increased farm productivity and reduction of food loss and waste — will reduce the number of people in chronic hunger by 314 million by 2030. Beyond hunger, 568 million people will be able to afford healthy diets, as shown in Figure 5. To target the remaining population, safety nets and targeted programs like school-feeding interventions are required. When adding such safety nets in the model, it is possible to cover the 2.4 billion remaining people without access to healthy diets.

Figure 4 Number of people (mio) removed from chronic undernourishment situation in 2030 (source: Preliminary results based on Laborde and Torero, 2021).

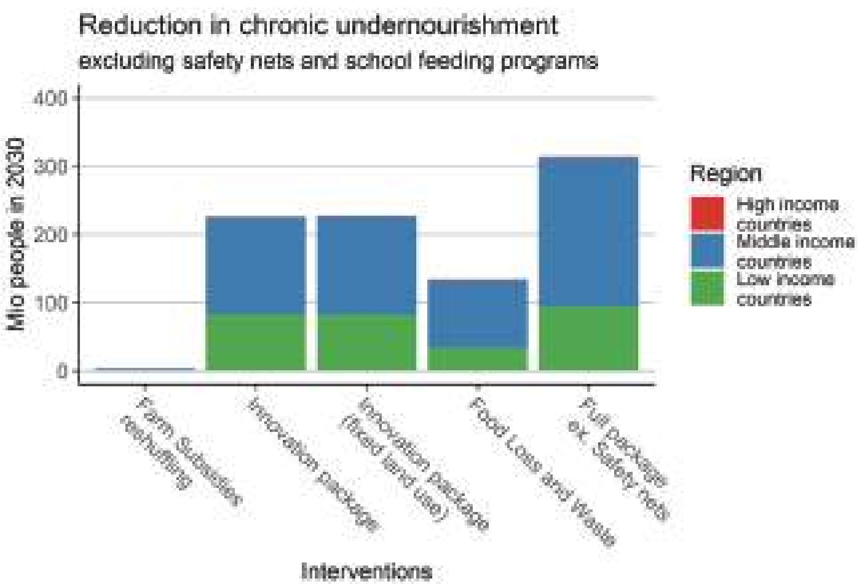
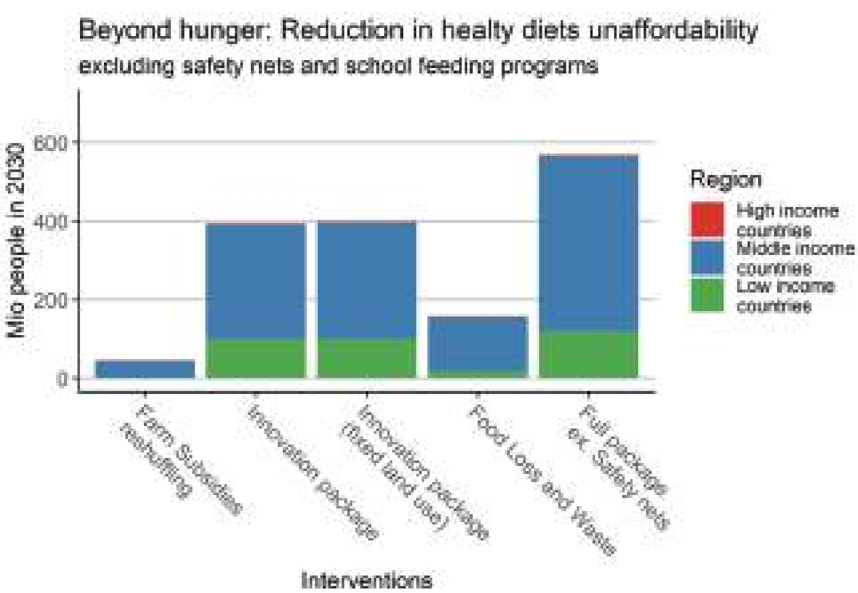


Figure 5 Number of people (mio) removed from not being able to access healthy diets by 2030 (source: Preliminary results based on Laborde and Torero, 2021)



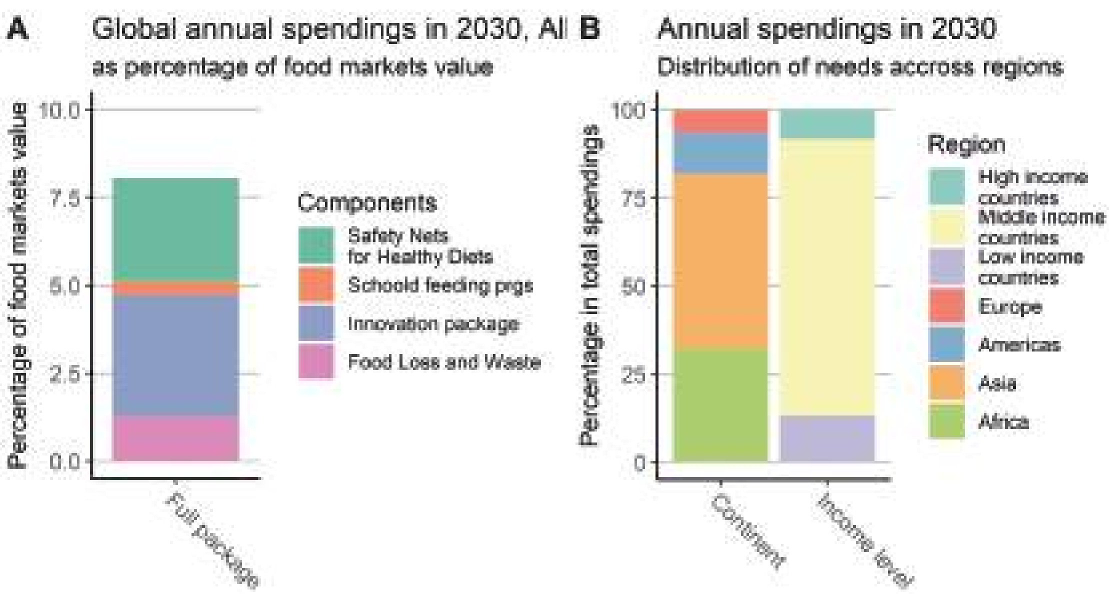
Achieving the end of widespread hunger requires significant resource mobilization, representing 8% of the size of food markets.[3] Figure 6 provides the breakdown of this total cost from all sources, public and private, by action (Panel A) and the distribution by group of countries (Panel B). The actions – referred to as "better choices" in Table 1 – including consumer incentives and farm subsidies re-purposing, do not contribute to the total costs because they are designed to be cost-neutral for the government and producers (farm subsidies) as well as consumers (food tax/subsidies) in each country. A related analysis of environmental effects of consumption change is provided by FABLE (2021).[82] The cost structure is dominated by the large investment in innovations for productivity, and in people, which impact the value chains and national economies (45%), and the social safety nets (36%). Clearly the two main items are different since the latter involves recurrent spending every year and will have to be managed and financed by governments alone.

The second panel in Figure 6 shows the distribution of the costs by region and hemispheres. Since the needs are unevenly distributed globally, a significant solidarity effort is required for global coordination, especially to support the transformation of food systems in low-income countries.

As previously shown, no single intervention can end malnourishment. The actions modeled will generate trade-offs in greenhouse gas emissions (emissions from agricultural production and net emissions from agriculture, forestry, and other land use, or AFOLU), chemical inputs (increased use of chemical inputs per hectare), biodiversity (reduction of forest habitat and agricultural land) and energy consumption. As shown in Figure 7, the levels of trade-offs across all interventions are relatively small.

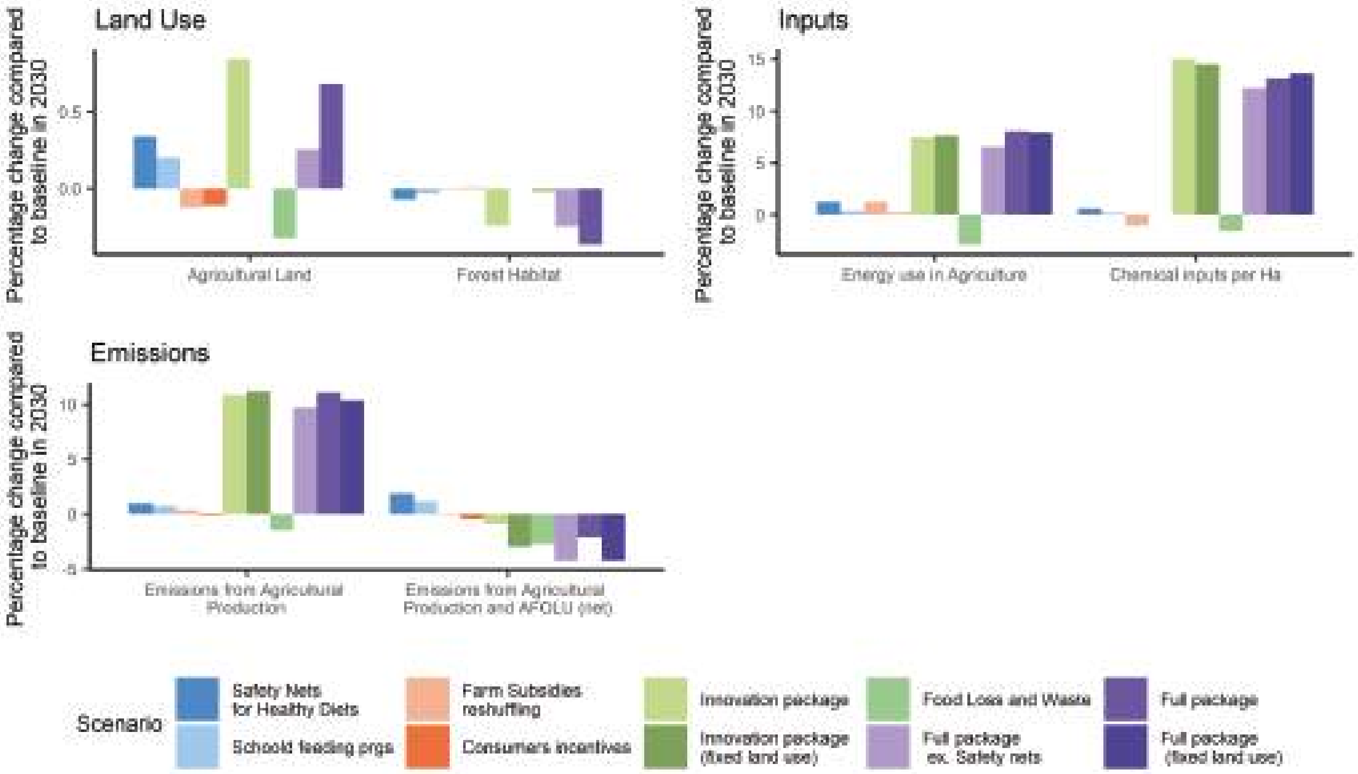
The effects indicate environmental improvement as a consequence of reducing food loss and waste. However, when it comes to net agricultural emissions and AFOLU, the effect is negative as is the case for forest land. This highlights the need for policies that can stimulate investments in innovation for carbon farming — growing carbon in soil and trees as a tradable commodity — and related payment schemes for ecosystems services, as indicated in section 3.5 concerning science and innovation actions above.

Figure 6 The cost of actions: magnitude and distribution (source: Preliminary results based on Laborde and Torero, 2021).



3 2030 spending and food market values, as estimated by the model to guarantee full consistency.

Figure 7 Impacts of actions on environmental indicators (source: Preliminary results based on Laborde and Torero, 2021)



5. ENABLING FOOD SYSTEMS TRANSFORMATION

Transformation of food systems that are under way do not guarantee that the food-related SDGs – especially SDG2 – will be achieved. There are fundamental conditions that are essential to enable and leverage food systems transformation to achieve desired objectives, including facilitating peace and security, and conflict resolution, full inclusion of marginalized and vulnerable populations, gender equity, sound governance at all levels from community to local to regional to national and international, and supportive global and national policies for public goods.[83] Modes of implementation need to especially focus on **finance, capacity, and governance.**

Finance: Enabling food systems transformations requires constant **investment in science** that has the potential to serve positive change in systems. In 2018, the world science "output" in terms of peer-reviewed publications was 4.04 million, and of these 14% related to agricultural and biological sciences (about 298,000) and environmental sciences (about 273,000).[84] Thousands of potentially game-changing insights are generated by the world science communities every year. More attention is needed to identify actionable insights for innovations and that requires strengthening capacity and innovative financing. Science systems have been decimated in many countries, especially in the global South. To tap the potentials of science, public funding of food systems science and related research partnerships need to expand. Governments need to change their low levels of spending on food systems-related research and innovation. We call on governments – especially in the global South – to review the level of their investments in food systems science and **allocate at least 1% of their food systems-related GDP to food systems science and innovation with a perspective to substantially exceed this target**. LDCs should be assisted in quickly reaching the equivalent of this target. About 20 years ago, African ministers responsible for science and technology had already committed to increase public expenditures on research and development to at least 1% of GDP per annum.[85] As basic sciences – for instance, bio-chemical and nutrition and health sciences – are becoming increasingly relevant for food systems, the investment in these must also be accelerated and systems of sharing of sciences for food systems expanded.[86] There are important new opportunities for engaging private sector science to address public goods in food systems innovations, particularly in partnership with the public sector.[87] The private sector here is a broad concept, ranging from semi-subsistence farmers to large corporations. It is often overlooked that the former are also proven innovators.[88] The knowledge of Indigenous

Peoples is another important component of local food systems' innovation landscape. Intellectual property rights protection issues require revisiting to align with sustainability expectations, especially for science opportunities that address overcoming hunger and malnutrition.[22] New institutional arrangements may be discussed for sharing intellectual property that could directly reduce hunger and address sustainability concerns.

The Food Systems Summit agenda needs to consider how the investments in the identified priority actions may be financed, and that is where **innovative finance** approaches shall be considered that economics research can explore. Research suggests that mobilizing the necessary financial resources may include a combination of actions, such as 1) additional – actually doubling – international development funds (ODA) to agricultural and rural development, food and nutrition security; 2) reallocation of agricultural subsidies towards investment for sustainable development and scaling up and redesigning social safety nets; 3) the initiation of a new dedicated "end hunger" fund, perhaps through expanded IDA; and 4) possibly financing innovative financial mechanisms such as "End Hunger Bonds" through support from incremental special drawing rights (SDRs).[89] The private sector should be part of the resource mobilization, expecting long-term returns from a more prosperous society. Research shall identify what combinations of finance may contribute to a sustainable financing of the food systems transformation.

Capacity: Of particular importance are investments for improving data, methods, models and tools for all food system components and actors, as well as building or enhancing (shared) research infrastructures related to (research) data, modeling platforms, observation and monitoring networks to support the required advances in research and innovation, especially in the global South.[90] Integrated global food system models are needed as existing models do not have consistent global coverage and are not designed to assess the impacts of all elements of food systems.[14] Besides global foresight work, strengthening national and – where possible – subnational/local, policy scenarios and foresight work is also necessary. More attention needs to be paid to strengthening local research capacities, expanding research collaboration among public and private sector research, and indigenous systems, sharing research infrastructure and data, developing more inclusive and equitable science partnerships and follow-up mechanisms, systematically learning what works and what can be scaled up and translating that knowledge into action, improving the efficiency in the way knowledge is generated and shared, and addressing intellectual property rights issues when they hinder innovations that can serve food and nutrition security, food safety, and sustainability goals.[18] With the increased recognition of their central role to achieving many development goals, food systems will be expected to perform a more complex set of activities, and this requires new and more appropriate holistic metrics. Protecting the freedom of science to innovate and experiment while adhering to ethical standards needs to be continually reinforced.

Because significant components of food systems are local, the Summit has to ensure that its outcomes and deliverables turn into positive local actions. This requires s**cience aligning with national and local agendas for implementation actions**. The proximity of science to decision-making is important to connect the timeliness and relevance of science to policy where and when it is needed. Similarly, the development of national and local infrastructure and expertise to effectively link science to decision-making is important. The science underpinning food systems transformation becomes more inter- and trans-disciplinary, more open to a wide range of innovations and their diverse stakeholders, and more appropriately configured and scaled to different contexts. Relatedly, it would be important to innovate and improve the methods for analyzing the performance of food systems (e.g. analyzing their impact on health, nutrition and sustainability goals) at different levels (local, national, global).

Transformation is not possible without science, and in many instances citizen participation in research and implementation can be very supportive for the transformation of farming, the application of new technologies, shifting to healthy diets, and other key elements of successful food systems transformation. **Citizen science** has an important role to play in inclusive food systems transformation, especially with farmers as co-designers directly participating in the development of innovations and with scientists being more open to and collaborating on fair terms with start-ups. **Indigenous Peoples knowledge systems** should be partnered with in such approaches.

The international sharing of science and participation of science in the follow-up to the Food Systems Summit as part of implementation agendas is vital. Proposals for international collaboration include supporting low- and middle-income countries to build and sustain capacities to acquire and deploy technologies through joint research, education and training programs. Beyond investing in capacities to undertake research, it will be important to also invest in capacities to act upon research: in other words, to put to effective use the knowledge and innovations that already exist (e.g. traditional and indigenous knowledge) or are generated from new research. This calls for investing in strengthening the skills of all food system actors, especially in emerging economies where these skills tend to be more limited. In many instances, what is lacking is actionable knowledge that may contribute to systemic changes, which requires supporting local innovations and encouraging and facilitating the co-creation/co-design of knowledge. In support of this, leading research organizations from world regions could form networks (or alliances) to share science and develop actionable knowledge supporting food systems transformations.

Governance and science-policy interface: In contrast to other subjects of global concern that were agreed upon at the Earth Summit in Rio in 1992, agriculture, food security and nutrition do not have an international agreement or convention to consolidate actions. Climate, biodiversity and desertification have their dedicated conventions and ensuing subsidiary bodies, secretariats and further protocols. Fueled by regular meetings of the conference of parties and underpinned by a solid science-policy interface, they have made enormous progress. Thus, we believe that the time has come to consider such a set of agreements and mechanisms for the complex area of food systems, obviously fully recognizing existing efforts and agents. The UNFSS may wish to consider opening a process for exploring a treaty on food systems. In a related manner, food systems science and policy need a stronger scientific framework for constructive and evidence-based interaction for moving ahead, not only for the Food Systems Summit 2021 but also for the long term.[91] At the national level, coherent national food systems research policies need to be better integrated into national development policies, such that countries develop their own context-specific food systems policies and strategies. At the international level, some have proposed strengthening the contribution of science to policy-making for transformational food systems with an Intergovernmental Scientific Advisory Panel, while others advocate strengthening and better connecting existing mechanisms.[92,17] We suggest exploring **options for an inclusive, global science-policy interface** (SPI) for a sustainable food system that connects national and global food systems concerns and will assist in an evidence-based follow-up to the proposed Summit actions and for the long term. This proposition is based on three considerations: (1) the growing complexity of food value chains from resource use to human nutrition and their increasing globalization, which urgently requires a new integrated approach drawing on all related science for sustainable agriculture, food and nutrition systems; (2) the absence of a comprehensive and timely system to collect, analyze and assess data on the diagnosis and technical, economic and social solutions to create long-term sustainable, affordable, nutritious and safe food systems; and (3) the limited or non-existent translation and traceability of scientific data and experiences into evidence-based policy that precludes the application of experiences across countries and regions.[93] Addressing these considerations requires a global mechanism that mobilizes the leading food systems scientists worldwide and across disciplines to support the SPI through co-production, open access, and communication of knowledge. The effective and independent participation of research communities from low-income countries and emerging economies in the SPI must be strengthened to enhance credibility, relevance and legitimacy. We call upon governments and UN agencies to initiate a process to explore options – existing[94] as well as new – for a global SPI for a sustainable food system. As such, this would be a concrete outcome of the UNFSS.

Science and policy have a lot to gain from cooperation but the independence of science must not be compromised to address policy and institutional opportunities and failures with evidence-based insights. Nonetheless, science that produces new insights also needs to constantly earn the trust of society, and in view of the cultural sensitivity of all matters related to food, policies and rules must assure confidence in scientific endeavors. Anti-science sentiments exist in parts of society. While pursuing new insights and truths, there are many issues on which scientists themselves do not agree, which sometimes irritates policy-makers and practitioners. Adhering to responsible and ethical principles, science must collaborate with a broad range of stakeholders. The improved quality and timeliness of science translation and communication for policy-makers and non-technical audiences are helpful, along with attention to ethics, peer review, scientific integrity and excellence, transparency and declarations of interest in science.

In closing, science, innovation, and technologies play critical roles among the measures to achieve food systems transformations. All sciences – natural sciences and social sciences, basic sciences and applied sciences – in collaboration with diverse traditional knowledge systems must deliver the innovations and make significant contributions for the necessary food systems transformation to achieve the SDGs, especially SDG2, and the complete 2030 Agenda.

ANNEX

Sources of contributions by Scientific Group and its partners as well as other relevant references

The Scientific Group draws on the science backgrounds of its members who are leaders in Food Systems related Science and the following sources for its emerging recommendations

1. The peer-reviewed background papers by the Scientific Group https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/
2. The about 40 Food Systems Summit Briefs on Big Cross Cutting Themes and Strategic Innovations by Partners of the Scientific Group (see list of Briefs at https://sc-fss2021.org/wp-content/uploads/2021/07/FSS_ScG_Briefs_draft_list_20-7-2021.pdf)
3. The Wealth of Recent Most Relevant Publications on Food Systems Related Research and Knowledge Community: More than 200 sources, clustered by the generic Food Systems Concept and Action Track Concept (https://sc-fss2021.org/materials/publications-and-reports-of-relevance-for-food-systems-summit/)
4. The Scientific Group engages in **peer review and evaluations of propositions by the Action Tracks** and insights from that also enter the Scientific Group's emerging conclusions. (see peer reviews on and by Scientific Group at (https://sc-fss2021.org/wp-content/uploads/2021/05/Evaluation_Peer_Review_and_Science_Advisory.pdf)

Re 1. Peer-reviewed background papers by the Scientific Group

https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/

Food Systems – Definition, Concept and Application for the UN Food Systems Summit
by Joachim von Braun, Kaosar Afsana, Louise O. Fresco, Mohamed Hassan, Maximo Torero
doi.org/10.48565/scfss2021-re63

Healthy diet – A definition for the United Nations Food Systems Summit 2021
by Lynnette M Neufeld, Sheryl Hendriks, Marta Hugas (March 2021)
doi.org/10.48565/scfss2021-e072

The True Cost and True Price of Food
by Sheryl Hendriks, Adrian de Groot Ruiz, Mario Herrero Acosta, Hans Baumers, Pietro Galgani, Daniel Mason-D'Croz, Cecile Godde, Katharina Waha, Dimitra Kanidou, Joachim von Braun, Mauricio Benitez, Jennifer Blanke, Patrick Caron, Jessica Fanzo, Friederike Greb, Lawrence Haddad, Anna Herforth, Danie Jordaan, William Masters, Claudia Sadoff, Jean-François Soussana, Maria Cristina Tirado, Maximo Torero, Matthew Watkins
https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf

Achieving Zero Hunger by 2030 – A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals
by Hugo Valin, Thomas Hertel, Benjamin Leon Bodirsky, Tomoko Hasegawa, Elke Stehfest (May 26, 2021) doi.org/10.48565/scgr2021-2337

Action Track 1 – Ensuring Access to Safe and Nutritious Food for All Through Transformation of Food Systems
by Sheryl Hendriks, Jean-François Soussana, Martin Cole, Andrew Kambugu, David Zilberman
doi.org/10.48565/scfss2021-wg92

Action Track 2 – Shift to Healthy and Sustainable Consumption Patterns
by Mario Herrero, Marta Hugas, Uma Lele, Aman Wira, Maximo Torero (April 2021)
doi.org/10.48565/scfss2021-9240

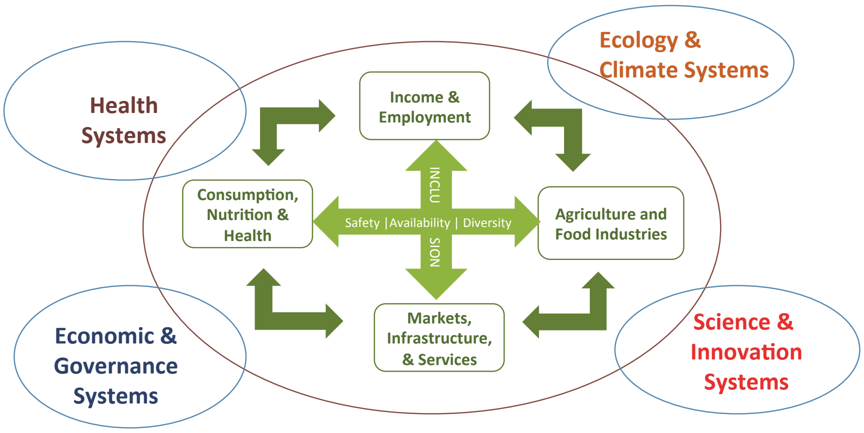
Action Track 3 – Boost Nature Positive Production
by Elizabeth Hodson, Urs Niggli, Kaoru Kitajima, Rattan Lal, Claudia Sadoff (April 2021)
doi.org/10.48565/scfss2021-q794

Action Track 4 – Advance Equitable Livelihoods
by Lynnette M. Neufeld, Jikun Huang, Ousmane Badiane, Patrick Caron, Lisa Sennerby Forsse (March 2021)
doi.org/10.48565/scfss2021-tw37

Action Track 5 – Building Resilience to Vulnerabilities, Shocks and Stresses
Thomas W. Hertel, Ismahane Elouafi, Frank Ewert and Morakot Tanticharoen (March 2021)
doi.org/10.48565/scfss2021-cz84

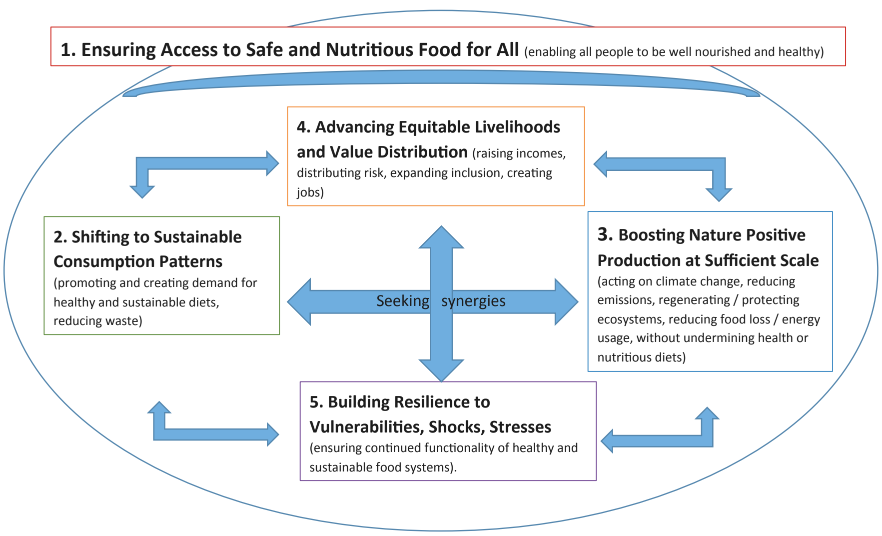
Re 3. Drawing on the Wealth of New Science Based Findings of Recent Most Relevant Publications of the Food Systems Related Research and Knowledge Community:

More than 200 sources, clustered by the generic Food Systems Concept
https://sc-fss2021.org/materials/publications-and-reports-of-relevance-for-food-systems-summit/



1. Food systems research
2. (broadly sorted by systems' components – only sources after 2016 considered)
3. Systems-wide research: Modelling Food Systems transformations- Synergies, Tradeoffs; Foresights – Policy Implications
4. Agriculture and Food Industries
5. Markets, Infrastructure and Services
6. Consumption, Nutrition and Health
7. Income and Employment

by the Action Track based Food Systems concept



1. Ensuring Access to Safe and Nutritious Food for All
2. Shifting to Sustainable Consumption Patterns
3. Boosting Nature Positive Production at Sufficient Scale
4. Advancing Equitable Livelihoods and Value Distribution
5. Building Resilience to Vulnerabilities, Shocks, Stresses

This Report was prepared by members of the Scientific Group.

REFERENCES

1. FAO. (2021) The White/Wiphala Paper on Indigenous Peoples' food systems. Rome. https://doi.org/10.4060/cb4932en
2. FAO, IFAD, UNICEF, WFP and WHO. 2021. The State of Food Security and Nutrition in the World 2021. Rome, FAO. http://www.fao.org/3/cb4474en/online/cb4474en.html
3. Klassen, S., & Murphy, S. (2020). Equity as both a means and an end: Lessons for resilient food systems from COVID-19. World Development, 136, 105104. https://doi.org/10.1016/j.worlddev.2020.105104
4. WHO (2020). Dietary recommendations: Nutritional requirements; Establishing human nutrient requirements for worldwide application. WHO, Geneva. https://www.who.int/news-room/fact-sheets/detail/food-safety
5. Dury S., Bendjebbar P., Hainzelin E., Giordano T., Bricas N. 2019. Food systems at risk. New trends and challenges. Rome: FAO-CIRAD-European Commission, 132 p. ISBN 978-2-87614-751-5https://doi.org/10.19182/agritrop/00080; FAO. 2018. The future of food and agriculture – Alternative pathways to 2050. Summary version. Rome. 60 pp. http://www.fao.org/3/CA1553EN/ca1553en.pdf
6. IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany.
7. HLPE (2017) Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 152 p. http://www.fao.org/3/a-i7846e.pdf
8. Food and Land use Coalition (2019): https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf
9. Bron, G. M., Siebenga, J. J., & Fresco, L. O. (2021). In the age of pandemics, connecting food systems and health: A Global One Health approach. Food Systems Summit Brief by Partners of Scientific Group. https://dx.doi.org/10.48565/scfss2021-z850
10. Webb. P, Flynn. D.J, Kelly. N.M, Thomas. S.M, & Benton, T.G, (2020), COVID-19 and Food Systems: Rebuilding for Resilience, Food Systems Summit Brief by Partners of Scientific Group. https://dx.doi.org/10.48565/scfss2021-g940
11. Moustier, P., Holdsworth, M., Seck, P. A., Renting, H., Caron, P., & Bricas, N. (2021). Priorities for inclusive urban food system transformations in the Global South. Food Systems Summit Brief by Partners of Scientific Group. doi.org/10.48565/3xdb-qq20
12. Osendarp, S., Akuoku, J., Black, R., Headey, D., Ruel, M., Scott, N., ... & Heidkamp, R. (2020). The potential impacts of the COVID-19 crisis on maternal and child undernutrition in low- and middle-income countries. Preprint under consideration at a Nature Portfolio Journal. https://doi.org/10.21203/rs.3.rs-123716/v1
13. von Braun, J., Zamagni, S., & Sorondo, M. S. (2020). The moment to see the poor. Science, 368(6488), 214. https://doi.org/10.1126/science.abc2255
14. J.von Braun, K.Afsana, L.O. Fresco, M.Hassan, M.Torero. (2021) Food Systems – Definition, Concept and Application for the UN Food Systems Summit. Scientific Group Report for the Food Systems Summit. doi.org/10.48565/scfss2021-re63
15. Webb, P., Benton, T. G., Beddington, J., Flynn, D., Kelly, N. M., & Thomas, S. M. (2020). The urgency of food system transformation is now irrefutable. Nature Food, 1(10), 584–585. https://doi.org/10.1038/s43016-020-00161-0; Mushtaq, S., Kath, J., Stone, R. et al. Creating positive synergies between risk management and transfer to accelerate food system climate resilience. Climatic Change 161, 465–478 (2020). https://doi.org/10.1007/s10584-020-02679-5
16. Allen, S., O. Badiane, L. Sene, and J. Ulimwengu. 2014. Government Expenditures, Health Outcomes, and Marginal Productivity of Agricultural Inputs: The Case of Tanzania. Journal of Agricultural Economics. Vol. 65, No. 3, 637-661; Wouterse, F. and O. Badiane. 2019. The role of health and educational attainment in agricultural production: Evidence from smallholders in Burkina Faso. Agricultural Economics, Volume 50, 4.
17. Hainzelin, E., Caron, P., Place, F., Dury, S., Echeverria, R., & Harding, A. (2021). How could science-policy interfaces boost food system transformation? Food Systems Summit Brief by Partners of Scientific Group https://dx.doi.org/10.48565/scfss2021-4y32
18. Fears. R, & Canales. C, (2021). The Role of Science, Technology and Innovation for Transforming Food Systems Globally. Food Systems Summit Brief by Partners of Scientific Group. http://doi.org/10.48565/scfss2021-q703
19. Diao, X., Reardon, T., Kennedy, A., DeFries, R.S., Koo, J., Minten, B., Takeshima,H & Thornton, P (2021), The Future of Small Farms: Innovations for Inclusive Transformation, Food Systems Summit Brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Small_Farms.pdf

20. Masters, W.A, Martinez,E.M, Greb, F, Herforth, A & Hendriks, S (2021). Cost and Affordability of Preparing a Basic Meal around the World Food Systems Summit Brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Cost_of_Basic_Meals.pdf
21. Center for Development Research (ZEF) of the University of Bonn in cooperation with the Food and Agriculture Organization of the United Nations (FAO). (2020). Investment Costs and Policy Action Opportunities For Reaching a World Without Hunger (SDG 2) http://www.fao.org/documents/card/en/c/cb1497en
22. Hendriks, S, Soussana, J.-F., Cole, M., Kambugu, A. & Zilberman, D. (2021) Ensuring Access to Safe and Nutritious Food for All Through Transformation of Food Systems Paper on Action Track 1. doi.org/10.48565/scfss2021-wg92
23. Hendriks, S., de Groot Ruiz, A., Acosta, M.H., Baumers, H., Galgani, P., Mason-D'Croz, P., Godde, C., Waha, K.,…. &, Watkins, M (June 1, 2021). The True Cost and True Price of Food,. Scientific Group Report for the Food Systems Summit. https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf
24. Hansen, J., Hellin, J., Rosenstock, T., Fisher, E., Cairns, J., Stirling, C., ... & Campbell, B. (2019). Climate risk management and rural poverty reduction. Agricultural Systems, 172, 28-46. https://doi.org/10.1016/j.agsy.2018.01.019
25. Miller, V., Yusuf, S., Chow, C. K., Dehghan, M., Corsi, D. J., Lock, K., Popkin, B., Rangarajan, S., Khatib, R., Lear, S. A., Mony, P., Kaur, M., Mohan, V., Vijayakumar, K., Gupta, R., Kruger, A., Tsolekile, L., Mohammadifard, N., Rahman, O., … Mente, A. (2016). Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: Findings from the Prospective Urban Rural Epidemiology (Pure) study. The Lancet. Global Health, 4(10), e695-703. https://doi.org/10.1016/S2214-109X(16)30186-3
26. Jaacks, L. M. 2019. Taxes on saturated fat, salt, and sugar improve the healthiness of grocery purchases, but changes are frustratingly small. The Lancet Public Health, 4(8): e363–e364. https://doi.org/10.1016/S2468-2667(19)30110-0 ; Micha, R., Karageorgou, D., Bakogianni, I., Trichia, E., Whitsel, L. P., Story, M., Peñalvo, J. L., & Mozaffarian, D. (2018). Effectiveness of school food environment policies on children's dietary behaviors: A systematic review and meta-analysis. PLOS ONE, 13(3), e0194555. https://doi.org/10.1371/journal.pone.0194555; Schreinemachers, P., Baliki, G., Shrestha, R. M., Bhattarai, D. R., Gautam, I. P., Ghimire, P. L., Subedi, B. P., & Brück, T. (2020). Nudging children toward healthier food choices: An experiment combining school and home gardens. Global Food Security, 26, 100454. https://doi.org/10.1016/j.gfs.2020.100454
27. Zilberman, D., Lu, L., & Reardon, T. (2019). Innovation-induced food supply chain design. Food Policy, 83, 289–297. https://doi.org/10.1016/j.foodpol.2017.03.010 ; Zarnowiecki, D., Mauch, C. E., Middleton, G., Matwiejczyk, L., Watson, W. L., Dibbs, J., Dessaix, A., & Golley, R. K. (2020). A systematic evaluation of digital nutrition promotion websites and apps for supporting parents to influence children's nutrition. International Journal of Behavioral Nutrition and Physical Activity, 17(1), 17. https://doi.org/10.1186/s12966-020-0915-1
28. Herrero, M., Hugas, M., Lele, U., Wira, A., & Torero, M. (2021). Shift to Healthy and Sustainable Consumption Patterns. Scientific Group Report for the Food Systems Summit: A Paper on Action Track 2. The Scientific Group for the UN Food System Summit 2021 https://dx.doi.org/10.48565/scfss2021-9240
29. Harris, J., Piters, B. D. S., McMullin, S., Bajwa, B., de Jager, I., & D Brouwer, I. (2021). Fruits and vegetables for healthy diets: Priorities for food system research and action. Food Systems Summit Brief by Partners of Scientific Group https://dx.doi.org/10.48565/scfss2021-ys30
30. van Zutphen, K.G., Barjolle, D., van den Berg, S., Gavin-Smith, B, Kraemer, K., Musard, C., Prytherch, H., Six, J., Winter, S & Woltering K Secondary Cities as Catalysts for Nutritious Diets in Low- And Middle-Income Countries. . Food Systems Summit Brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Secondary_Cities.pdf
31. Hirvonen, K., Bai, Y., Headey, D., & Masters, W. A. (2020). Affordability of the EAT–Lancet reference diet: a global analysis. The Lancet Global Health, 8(1), e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4 , Headey, D. D., & Alderman, H. H. (2019). The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. The Journal of Nutrition, 149(11), 2022-2033. https://doi.org/10.1093/jn/nxz158
32. See at https://foodperiodictable.org/about/
33. Kau, A., Ahern, P., Griffin, N. et al. Human nutrition, the gut microbiome and the immune system. Nature 474, 327–336 (2011). https://doi.org/10.1038/nature10213
34. Downs, S., & Demmler, K. M. (2020). Food environment interventions targeting children and adolescents: A scoping review. Global Food

Security, 27, 100403 https://doi.org/10.1016/j.gfs.2020.100403 .
35. Mirzabaev, A., Olsson, L., Kerr, R. B., Pradhan, P., Guadalupe, M., Ferre, R., & Lotze-Campen, H. Climate Change and Food Systems. Food Systems Summit Brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/05/FSS_Brief_Climate_Change_and_Food_Systems.pdf
36. Sperling, F., Havlik, P., Denis, M., Valin, H., Palazzo, A., Gaupp, F., & Visconti, P. (2020). Transformations within reach: Pathways to a sustainable and resilient world-Resilient Food Systems. http://pure.iiasa.ac.at/16822
37. Kemmerling, B., Schetter, C. & Wirkus, L. (2021) Addressing Food Crises in Violent Conflicts. Systems Summit Brief by Partners of Scientific Group. https://dx.doi.org/10.48565/scfss2021-h009
38. Sultan Barakat, Sansom Milton. 2020. Localisation Across the Humanitarian-Development-Peace Nexus.
Journal of Peacebuilding & Development. Vol 15, Issue 2, 2020 https://doi.org/10.1177/1542316620922805
39. Bhutta, Z. A., Das, J. K., Rizvi, A., Gaffey, M. F., Walker, N., Horton, S., Webb, P., Lartey, A., & Black, R. E. (2013). Evidence-based interventions for improvement of maternal and child nutrition: What can be done and at what cost? The Lancet, 382(9890), 452–47;
Hidrobo, M., Hoddinott, J., Kumar, N., & Olivier, M. (2018). Social Protection, Food Security, and Asset Formation. World Development, 101, 88–103. Ruel, M. T. &, Alderman, H., & Maternal and Child Nutrition Study Group. (2013). Nutrition-sensitive interventions and programmes: How can they help to accelerate progress in improving maternal and child nutrition? The Lancet, 382(9891), 536-551.
40. Zimmermann, A & Rapsomanikis, G (2021) Trade and Sustainable Food Systems. Food Systems Summit Brief by Partners of Scientific Group. http://doi.org/10.48565/scfss2021-zq03
41. Hodson, E., Urs, N., Kaoru, K., Lal, R., Sadoff, C (2021), Boost Nature Positive Production: A paper on Action Track 3. The Scientific Group for the UN Food System Summit 2021, 2021. https://dx.doi.org/10.48565/scfss2021-q794; Hertel, T W., Elouafi, I., Frank, E., Morakot, T, (2021), Building Resilience to Vulnerabilities, Shocks and Stresses: A paper on Action Track 5. The Scientific Group for the UN Food System Summit 2021. https://dx.doi.org/10.48565/scfss2021-cz84
42. Daily, G. C., & Polasky, S. (2019). How do we stem biodiversity loss? In Biological Extinction: New Perspectives (pp. 332-357). Cambridge University Press. https://doi.org/10.1017/9781108668675.015; Rahman, H. M., & Hickey, G. M. (2019). What does autonomous adaptation to climate change have to teach public policy and planning about avoiding the risks of maladaptation in Bangladesh? Frontiers in Environmental Science, 7, 2. https://doi.org/10.3389/fenvs.2019.00002
43. Jensen, E.S., Carlsson, G. & Hauggaard-Nielsen, H. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. Agron. Sustain. Dev. 40, 5 (2020). https://doi.org/10.1007/s13593-020-0607-x
44. Neufeld, L M., Jikun. H., Ousmane, B., Patrick C., Forsse, L.S, (2021) Advance Equitable Livelihoods: A paper on Action Track 4. The Scientific Group for the UN Food System Summit 2021. https://dx.doi.org/10.48565/scfss2021-tw37; Lal, R. (2017). Improving soil health and human protein nutrition by pulses-based cropping systems. Advances in Agronomy, 145, 167-204. https://doi.org/10.1016/bs.agron.2017.05.003
45. van Zonneveld, M., Volk, G. M., Dulloo, M. E., Kindt, R., Mayes, S., Quintero, M., ... & Guarino, L. (2021). Safeguarding and using fruit and vegetable biodiversity. Food Systems Summit Brief by Partners of Scientific Group https://dx.doi.org/10.48565/scfss2021-rz27
46. Schmitz, S., Barrios, R., Dempewolf, H., Guarino, L., Lusti, C., & Muir, J. (2021). Crop Diversity, its Conservation and Use for Better Food Systems. The Crop Trust Perspective. Food Systems Summit Brief prepared by Research Partners of the Scientific Group for the Food Systems Summit. https://dx.doi.org/10.48565/scfss2021-j983
47. Niggli, U., Sonnevelt, M., & Kummer, S. (2021). Pathways to advance agroecology for a successful transformation to sustainable food systems. Food Systems Summit Brief prepared by Research Partners of the Scientific Group doi.org/10.48565/scfss2021-wf70; Snapp, S., Kebede, Y., Wollenberg, E., Dittmer, K. M., Brickman, S., Egler, C., & Shelton, S. (2021). Delivering climate change outcomes with agroecology in low-and middle-income countries: evidence and actions needed. . Food Systems Summit Brief prepared by Research Partners of the Scientific Group. http://doi.org/10.48565/scfss2021-2420
48. Alae-Carew, C., Nicoleau, S., Bird, F. A., Hawkins, P., Tuomisto, H. L., Haines, A., ... & Scheelbeek, P. F. (2020). The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. Environmental Research Letters, 15(2), 023002. https://doi.org/10.1088/1748-9326/ab5cc0

49. Donald Bundy, Susan Horton, Dean Jamison, George Patton, Nilanthi de Silva (editors). 2018. Re-Imagining School Feeding: A High Return Investment in Human Capital and Local Economies. DCP3 and WFP. http://www.dcp-3.org/schoolfeeding
50. Trigo, E., Chavarria, H., Pray, C., Smyth, S. J., Torroba, A., Wesseler, J., Zilberman, D., Martinez, J.F. (2021) The Bioeconomy and Food Systems Transformation: Food Systems Summit Brief prepared by Research Partners of the Scientific Group http://doi.org/10.48565/scfss2021-w513
51. Dobermann, A., Bruulsema, T., Cakmak, I., Gerard, B., Majumdar, K., McLaughlin, M., Reidsma, P., Vanlauwe, B., Wollenberg, L., Zhang, F., Zhang, X. A New Paradigm for Plant Nutrition: Food Systems Summit Brief prepared by Research Partners of the Scientific Group. http://doi.org/10.48565/SCFSS2021-HG55
52. Van der Ploeg, J. D., Barjolle, D., Bruil, J., Brunori, G., Madureira, L. M. C., Dessein, J., ... & Wezel, A. (2019). The economic potential of agroecology: Empirical evidence from Europe. Journal of Rural Studies, 71, 46-61. https://doi.org/10.1016/j.jrurstud.2019.09.003
53. World Economic Forum. 2021. The Global Risks Report 2021. http://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf
54. Fuglie, K., Gautam, M., Goyal, A., & Maloney, W.F. (2020). Harvesting Prosperity: Technology and Productivity Growth in Agriculture. Washington, DC: World Bank. doi:10.1596/978-1-4648-1393-1
55. Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Le Hoang, A., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J., Taboada, M. A., Manning, F. C., Nampanzira, D., Arias-Navarro, C., Vizzarri, M., House, J., … Arneth, A. (2020). Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology, 26(3), 1532–1575. https://doi.org/10.1111/gcb.14878
56. van Vliet, S., Kronberg, S. L., & Provenza, F. D. (2020). Plant-Based Meats, Human Health, and Climate Change. Frontiers in Sustainable Food Systems, 4, 128. https://doi.org/10.3389/fsufs.2020.00128
57. Jensen ES, Carlsson G and Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global- scale analysis. Agronomy for Sustainable Development, 40(1), 5. https://doi.org/10.1007/s13593-020-0607-x
58. Lal, R. (2017). Improving soil health and human protein nutrition by pulses-based cropping systems. In Advances in Agronomy (Bd. 145, S. 167–204). Elsevier. https://doi.org/10.1016/bs.agron.2017.05.003
59. Pretty, J., Benton, T.G., Bharucha, Z.P. et al. Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1, 441–446 (2018). https://doi.org/10.1038/s41893-018-0114-0
60. Padulosi S., Phrang Roy and Francisco J. Rosado-May (2019). Supporting Nutrition Sensitive Agriculture through Neglected and Underutilized Species - Operational Framework. Bioversity International and IFAD, Rome, Italy. 39 pp.
61. Lal, R. (2020). Managing Organic Matter Content for Restoring Health and Ecosystem Services of Soils of India, Journal of the Indian Society of Soil Science, Vol. 68, No. 1, pp 1-15 (2020) DOI: 10.5958/0974-0228.2020.00001.8
62. Webb, P., Flynn, D. J., Kelly, N. M., & Thomas, S. M. (2021). The Transition Steps Needed to Transform Our Food Systems. Food Systems Summit Brief prepared by Research Partners of the Scientific Group. http://doi.org/10.48565/scfss2021-hz63
63. Benfica, R., Chambers, J., Koo, J., Nin-Pratt, A., Falck-Zepeda, J., Stads, G. J., & Arndt, C. (2021). Food System Innovations and Digital Technologies to Foster Productivity Growth and Rural Transformation. Food Systems Summit Brief prepared by Research Partners of the Scientific Group https://dx.doi.org/10.48565/scfss2021-6180
64. Thornton, P. K., Kristjanson, P., Förch, W., Barahona, C., Cramer, L., & Pradhan, S. (2019). Is agricultural adaptation to global change in lower-income countries on track to meet the future food production challenge? Global Environmental Change, 52, 37-48. https://doi.org/10.1016/j.gloenvcha.2018.06.003
65. Le Q.B., Nkonya E., Mirzabaev A. (2016) Biomass Productivity-Based Mapping of Global Land Degradation Hotspots. In: Nkonya E., Mirzabaev A., von Braun J. (eds) Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer, Cham. https://doi.org/10.1007/978-3-319-19168-3_4
66. IPCC, 2019: Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla et l., (eds.)]. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf
67. Ringler, C., Agbonlahor, M., Baye, K., Barron, J., Hafeez, M., Lundqvist, J., ... & Uhlenbrook, S. (2021). Water for Food Systems and Nutrition.

Food Systems Summit Brief prepared by Research Partners of the Scientific Group. doi.org/10.48565/scfss2021-tg56

68. Mirzabaev, A., et al 2019: Desertification. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, et al. (eds.)]. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/06_Chapter-3.pdf
69. Shukla, et al (2019). Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf
70. Smith, P. et al. 2019: Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, et al., (eds.)]. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/09_Chapter-6.pdf
71. Guerra, C.A., Heintz-Buschart, A., Sikorski, J. et al. Blind spots in global soil biodiversity and ecosystem function research. Nat Commun 11, 3870 (2020). https://doi.org/10.1038/s41467-020-17688-2
72. Bernard, B., Lux, A. How to feed the world sustainably: an overview of the discourse on agroecology and sustainable intensification. Reg Environ Change 17, 1279–1290 (2017). https://doi.org/10.1007/s10113-016-1027-y; Pretty, J., Benton, T.G., Bharucha, Z.P. et al. Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1, 441–446 (2018). https://doi.org/10.1038/s41893-018-0114-0
HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf
73. Olsson, L. et al. (2019) Land Degradation. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, et al., (eds.). https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/07_Chapter-4.pdf
74. Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N. J., Bauch, S., ... & Wunder, S. (2014). Environmental income and rural livelihoods: a global-comparative analysis. World development, 64, S12-S28. https://doi.org/10.1016/j.worlddev.2014.03.006
75. Azam-Ali, S., Ahmadzai, H., Choudhury, D., Goh, E. V., Jahanshiri, E., Mabhaudhi, T., ... & Olutayo, A. (2021). Marginal areas and indigenous people–Priorities for research and action. Food Systems Summit Brief Prepared by Partners of the Scientific Group https://dx.doi.org/10.48565/fd4f-rk35
76. Leape, J., Micheli, F., Tigchelaar, M., Allison, E. H., Basurto, X., Bennett, A., Bush, S. R., Cao, L., ..., & Wabnitz, C. C.C. 2021. The Vital Roles of Blue Foods in the Global Food System, - Protect and develop the potential of blue foods to help end malnutrition, Food Systems Summit Brief Prepared by Partners of the Scientific Group https://dx.doi.org/10.48565/scfss2021-bg71
77. Costello, C., L. Cao, S. Gelcich et al. 2019. The Future of Food from the Sea. Capture Fisheries: Current status and trends, Washington, DC: World Resources Institute. Available online at www.oceanpanel.org/future-food-sea
78. International Food Policy Research Institute. 2020. 2020 Global Food Policy Report: Building Inclusive Food Systems. Washington, DC: International Food Policy Research Institute. - Reshaping Food Systems https://doi.org/10.2499/9780896293670
79. Taylor, B; Tonnang, HEZ; Beale, T; Holland, W; Oronje, M; Abdel-Rahman, EM; Onyango, D., Finegold, C; Zhu, J; Pozzi, S, Murphy, ST (2021) Leveraging data, models & farming innovation to prevent, prepare for & manage pest incursions: Delivering a pest risk service for low-income countries. Food Systems Summit Brief Prepared by Partners of the Scientific Group. https://dx.doi.org/10.48565/scfss2021-ty56
80. Lal, R. Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Sec. 12, 871–876 (2020). https://doi.org/10.1007/s12571-020-01058-3
81. Malabo Montpellier Panel (2019). Byte by Byte: Policy Innovation for Transforming Africa's Food System with Digital Technologies, Dakar. June 2019. DOI: https://doi.org/10.2499/9780896296848
82. FABLE (2021). Environmental and agricultural impacts of dietary shifts at global and national scales. FABLE Policy Brief July 2021. Paris: Sustainable Development Solutions Network (SDSN).

83. Global Panel on Agriculture and Food Systems for Nutrition. (2020). Future Food Systems: For people, our planet, and prosperity. https://www.glopan.org/foresight2/; International Food Policy Research Institute (IFPRI). (2020). Global Food Policy Report: Building Inclusive Food Systems. https://doi.org/10.2499/9780896293670
84. Scimago journal and country rankings for 2018
85. Declaration of the first NEPAD Ministerial conference on Science and Technology, 7 November 2003, Johannesburg, South Africa https://sarpn.org/documents/d0000614/index.php
86. Beintema, N., Pratt, A. N., & Stads, G.-J. (2020). Key Trends in Global Agricultural Research Investment. ASTI Program Note. https://www.asti.cgiar.org/sites/default/files/pdf/Global-update-ASTI-note.pdf; von Braun, J. (2020) "Transforming Food Systems – the challenges of food security, malnutrition, climate change, ecosystems degradation, well-being" Presentation at the European Union - FAO Strategic Dialogue (May 06, 2021) https://sc-fss2021.org/wp-content/uploads/2021/05/EU_FAO_JvonBraun_Keynote_6-5-2021.pdf
87. Herrero, M., Thornton, P.K., Mason-D'Croz, D. et al. Innovation can accelerate the transition towards a sustainable food system. Nat Food 1, 266–272 (2020). https://doi.org/10.1038/s43016-020-0074-1
88. Tambo, J.A. T. Wünscher. (2017) Farmer-led innovations and rural household welfare: Evidence from Ghana. Journal of Rural Studies, 2017
89. von Braun, J., Bezawit C., Torero M. C., Laborde, D., & Carin, S (2021). Ending Hunger by 2030 – policy actions and costs, Food Systems Summit Brief prepared by Research Partners of the Scientific Group for the Food Systems Summit 2021 https://dx.doi.org/10.48565/scfss2021-kz31;
90. Díaz-Bonilla, E. (2021). Financing SGD2 and Ending Hunger. Food Systems Summit Brief prepared by Research Partners of the Scientific Group for the Food Systems Summit 2021 https://dx.doi.org/10.48565/scfss2021-ba75
Inter-Academy Partnership. (2018). Opportunities for future research and innovation on food and nutrition security and agriculture: The Inter-Academy Partnership's global perspective. https://www.interacademies.org/sites/default/files/publication/iap_fnsa_global_web_complete_28nov.pdf
91. von Braun, J. (2018). Global Institutions: Governance Reform for Food, Nutrition, and Agriculture. 2018 Global Food Policy Report, 62–71 https://doi.org/10.2499/9780896292970_08;
92. Inter-Academy Partnership. (2018). Opportunities for future research and innovation on food and nutrition security and agriculture: The Inter-Academy Partnership's global perspective.
von Braun, J., & Kalkuhl, M. (2015). International Science and Policy Interaction for Improved Food and Nutrition Security: Toward an International Panel on Food and Nutrition (IPFN). ZEF Working Paper Series, 142(October).
93. Hendriks, S. L., Bekele, E., Chaibi, T., Hassan, M., Miano, D. W., & Muyonga, J. H. (2021). The Role of Science, Technology, and Innovation for Transforming Food Systems in Africa. doi.org/10.48565/scfss2021-a948;
Hodson de Jaramillo, E., Trigo, E. J., & Campos, R. (2021). The Role of Science, Technology and Innovation for Transforming Food Systems in Latin America and the Caribbean. doi.org/10.48565/scfss2021-6w45;
Moughan, P. J., Chamovitz, D. A., Ayyappan, S., Tanticharoen, M., Lal, K., & Kim, Y. H. (2021). The Role of Science, Technology, and Innovation for Transforming Food Systems in Asia. doi.org/10.48565/scfss2021-tf41;
Fan, S., Huang, J., Zhang, F., Zhao, W., Song, H., Nie, F., ... & Cong, W. (2021). Transforming Chinese Food Systems for both Human and Planetary Health. doi.org/10.48565/scfss2021-vq06;
Serova, E., Orlova, N., Popov, V., Petukhova, M., Osmakova, A., Kobiakov, O., ... & Tolmachev, P. (2021). Key Areas of the Agricultural Science Development in Russia in the Context of Global Trends and Challenges. doi.org/10.48565/scfss2021-6265;
Gulati, A., Paroda, R., Sanjiv, P., Narain, D., & Ghanwat, A. (2021). Food System in India: Challenges, Performance and Promise. doi.org/10.48565/scfss2021-b823, Food Systems Summit Brief prepared by Research Partners of the Scientific Group for the Food Systems Summit 2021
94. Including the CGIAR (https://www.cgiar.org/), the Global Forum on Agricultural Research and Innovation (GFAR) https://www.gfar.net/), the High Level Panel of Experts on Food Security and Nutrition (HLPE) (http://www.fao.org/cfs/cfs-hlpe), and the InterAcademy Partnership (IAP) (https://www.interacademies.org/)

UNITED NATIONS
FOOD SYSTEMS
SUMMIT 2021
The Scientific Group for the
UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

FOOD SYSTEMS – DEFINITION, CONCEPT AND APPLICATION FOR THE UN FOOD SYSTEMS SUMMIT

by Joachim von Braun, Kaosar Afsana, Louise O. Fresco,
Mohamed Hassan and Maximo Torero

ABSTRACT

The UN Food Systems Summit seeks to alter food systems to be healthier, safer, more sustainable, efficient, and equitable. This paper aims to inform the public and stakeholders interested in the Food Systems Summit about concepts and definitions of food systems and determinants of their change. To foster a clear understanding of food systems, especially regarding the upcoming UN Food Systems Summit, we first present a general food systems concept. We then introduce a concept based on science that provides a definition that the UN Food Systems Summit can use with the five goal-oriented Action Tracks (serving SDG2) and their interlinkages. We suggest a food system definition that encompasses food systems thinking and the

ABOUT THE AUTHORS

Joachim von Braun (Germany), Chair of the Scientific Group, Director of the Center for Development Research (ZEF), Bonn University, and Professor for economic and technological change.

Kaosar Afsana (Bangladesh) Vice Chair of the Scientific Group, BRAC James P Grant School of Public Health, BRAC University, Dhaka.

Louise Fresco (Netherlands) Vice Chair of the Scientific Group, President of the Executive Board, Wageningen University & Research.

Mohamed Hassan (Sudan) Vice Chair of the Scientific Group, President of The World Academy of Sciences for the advancement of science in developing countries (TWAS).

Maximo Torero (Peru), ex-officio Member Chief Economist of the Food and Agriculture Organization of the United Nations (FAO).

broad set of actors and drivers, embedding the concept of sustainability within it.

1. INTRODUCTION

The UN Food Systems Summit convenes to bring about actions that promise change towards achieving healthier and more sustainable and equitable food systems. As we head towards the Summit, the very concept of food systems needs to be clearly understood for fruitful deliberations and ultimately actions. Therefore, the main purpose of this paper is to inform about concepts and definitions of food systems. In this context, it is necessary to clarify the drivers and mechanisms of change of food systems. Conceptualising systems' change is relevant for policy opportunities and for setting ambitious goals for the Food Systems Summit.

Food systems exist at different scales: global, regional, national and local. The local food systems around the world are very diverse and location-specific. They share some key features, but any attempt to change them should reflect their uniqueness. Change in food systems comes about through external and internal drivers as well as through feedback mechanisms between these drivers. These feedback mechanisms may be short or long term, and some may come with long delays, such as the impact of greenhouse gas emissions manifesting in climate change. External drivers are forces outside of the food systems, for example, forces in climate or health systems. Internal drivers are forces within the food systems, for example productivity gains as a consequence of innovations. Population growth, urbanisation, conflicts, and geopolitical instabilities are fundamental external drivers interacting with changes in food systems. Changes in consumer habits, for instance as a result of rising incomes, are another driver of great importance. Markets, trade, and infrastructures – increasingly combined with digitisation – are cutting across internal and external drivers of food systems' change. Developments in the many scientific disciplines related to food systems, innovations, and technologies as well as their interlinkages with policies greatly impact food systems' change. These determinants of changes are also driven by the interests, needs, and accomplishments of farming communities, the agricultural inputs and food industries, distributors, and consumers' demand. Purposeful policy interventions attempt to influence all of these forces of change, or their consequences, such as the loss of biodiversity. Policies, however, are also partly driven and re-defined by these drivers. Moreover, there are long-term natural and evolutionary biological change processes that also impact the multiple interactions within food systems. All drivers affecting food systems are subject to multiple systemic risks of hazards carrying uncertainties that often materialise in sudden occurrences of events. This is the case with COVID-19 and with locust swarms for example. Uncertainties, and more specifically their impacts on food systems, are difficult to predict and measure, but prevention with risk management and anticipation, including emergency preparedness and capacity to face them, may reduce their impacts.

Food systems have been continuously subject to change and adaptation since they evolved with humankind, though change has been especially dramatic in the past 200 years. Food systems are bound to further change in the future given that we are developing towards an ever more urban society and that the world population will possibly be stabilising at about 9 to 10 billion people only by the end of this century (Lutz 2020).

The way in which changes in food systems impact sustainability in its diverse social, economic, and environmental dimensions must be of key interest to us. The role of science and innovation is essential here, as some of the conflicting issues about food systems' changes can be remedied by innovations. We can note at the outset that there is an accelerating momentum worldwide, including in the United Nations, to adopt systems approaches to bring consumption and production patterns together to achieve sustainable development through an integrated approach to food systems.[1]

Food systems are incredibly diverse. Consider that the food systems of mega-cities in Africa, such as Kinshasa, are very different from the food systems of mega-cities in Asia, such as Tokyo. The food systems of rural South Asia with its public distribution systems at village levels are very different from food systems of rural Europe with its supermarket penetration. And the food systems of small island nations dependent on food imports in the Caribbean are very different from the food systems of large middle-income countries with domestic food industries and significant export potentials in South America.

1 At the Rio+20 UN Conference on Sustainable Development in 2012, Heads of State converged around the idea that fundamental changes in our production and consumption patterns are indispensable to achieving long-term sustainable development. The realization that a global shift towards SCP would require the commitment of diverse actors across the globe spurred Heads of State at Rio+20 to adopt the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns (10YFP). See at: 10YFP Framework of Programmes on Sustainable Consumption and Production Patterns.

With this paper we aim to inform the interested Food Systems Summit public. We discuss both change that happens anyway (i.e. drawing on a so-called "positive theory" of systems) and change that is actively pursued and goal-oriented, especially within the context of the Sustainable Development Goals (SDGs) by, for instance, setting new norms (i.e. drawing on normative theories of systems). Food systems are not just technically functioning mechanistic clock works, but are embedded in values and cultures that need to be considered when "systems transformations" are proposed. Our goal is to assist in the understanding of food systems, their dynamics, their indirect effects, responses to exogenous influences, and impacts of policies through system linkages. Finally, we seek to relate these concepts in helpful ways to the purpose of the UN Food Systems Summit.

2. A GENERAL FOOD SYSTEMS CONCEPT

Theory and Criteria

A practical definition of food systems should meet two essential criteria:

(1) it should be suitable for the purpose at hand, which is to support the global and national collective efforts to bring about positive change in food systems, by accelerating progress on meeting the 2030 Agenda and the SDGs; and

(2) it should be sufficiently precise to define the domains for policy and programmatic priorities, and it should be sufficiently general to not exclude any aspects of the economic, social, and environmental dimensions of sustainability.

The significance of criterion (1) is that the definition should guide not only scientific inquiry, but also actions of all types, towards a common purpose, i.e. food systems change and in the long run even food systems transformation. The point of criterion (2) is to avoid the intellectual hubris that accompanies many efforts of characterising and graphically depicting food systems' complexities in great detail. Efforts to map food systems visually may help scientists as well as decision makers to identify key interactions and the mechanisms, both natural and social, which regulate those interactions. Nonetheless, food systems' maps that try to be fully comprehensive tend to collapse under the density and complexity of the interactions to be described and analysed. At the other extreme, food systems' maps and models that focus too narrowly on a reduced set of phenomena gain apparent explanatory power at the price of realism, adequacy or the exclusion of important economic, social or environmental forces. There is no clearly defined pathway out of this dilemma. Much depends on the relevant policy question as well as on the context and scale of the food systems under consideration.

We distinguish between systems theory and systems thinking (Box 1) and suggest a definition of food systems that acknowledges the functional relationships in systems and is normative in relation to a given set of core objectives, such as the SDGs. This approach should not neglect basic principles of systems theory. For instance, a system that has no defined boundaries or whose building blocks connected by linkages and feedback mechanisms are ill-defined is a fuzzy concept.

Food systems' boundaries refer to specific scales as pointed out above (local, national, regional, and global), for different contexts (e.g. urban, rural), and may be shaped by interlink with other systems, such as the (decentralised) governance system and the health system. Boundaries may also dynamically change, for instance due to technology or infrastructure. However, as important as this established theoretical foundation is advancement of systems thinking, which entails broadening perspectives around food systems (such as planetary health), and within food systems (such as the important roles of culture and values).

Box 1: On Systems Theory and Systems Thinking

Systems theory and system dynamics are established concepts that may assist in conceptualising food systems yet are conceptually rather restrictive. Systems theory is the study of systems. Important conceptualisations stem from W. Forrester who is a founder of the field of system concepts and dynamics (Radzicki and Taylor 2008). Forrester argues that a system is composed of regularly interacting or interrelating groups of activities. System dynamics is a methodology to frame, understand and discuss complex issues and problems. The best-known system dynamics model is probably The Limits to Growth (Meadows et al. 1972).

Systems thinking is a way of looking at the world rather than a description of how the world is. The term "food systems" invites us to think about a broader set of valued outcomes such as nutrition and health, livelihoods, and planetary health, a broader set of factors that can influence these outcomes, and synergies and trade-offs between all of these. People's values matter for how food systems thinking is shaped and in turn may shape policies[2].

2 An important emphasis is placed on food and agriculture that are intimately connected to people's values. People differ in the values they hold relative to food and agriculture, and these value differences correlate with their behaviour as consumers and as citizens (further on these important aspects see OECD 2021)

Definitions of Current and Future Food Systems

Food systems embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products that originate from agriculture (incl. livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded (building on definitions by FAO (2018) and others). Production includes, of course, farming communities but also pre-production actors, for example input industries producing fertilisers or seeds. The range of actors importantly includes science, technology, data, and innovation actors. They are partly integral to the food systems, and partly outside but of great influence, for instance, embedded in life science and health systems research. In food industries' processing, foods and non-foods result from interlinked value chains. Other relevant food systems actors include, for example, public and private quality and safety control organisations.

A sustainable food system is one that contributes to food security and nutrition for all in such a way that the economic, social, cultural, and environmental bases to generate food security and nutrition for future generations are safeguarded. It should be noted that desirable food systems are necessary but not sufficient to assure good nutrition, as even the best food system cannot assure good nutrition in a situation of poor hygiene, unclean drinking water, poor childcare, and widespread infectious diseases. Moreover, the availability of plentiful and healthy food does not guarantee adequate consumption patterns or prevent excess body weight. The concept of a sustainable food system entails normative aspects because food systems use resources that typically do not offer absolute levels of sustainability. Thus, sustainable food systems incorporate an understanding of sustainability that reflects relative change in the sense of a change towards more versus less sustainability compared to a previous situation.

The concept of food systems transformation has been linked to the aspirations of the 2030 Agenda and refers to the objective of pursuing fundamental change of food systems, for instance, to aim for climate neutrality and achieving the SDGs. For analytical and monitoring purposes we suggest a more neutral, evidence-based terminology, which may distinguish between status and systems dynamics by referring to evolution, transition, and transformation. The idea of transformation as commonly used can refer to any large-scale change, whether intended or not, and whether beneficial or not to a specific goal, context, or geography. The Global Sustainable Development Report defined transformation as "a profound and intentional departure from business as usual" with the intentional departure being specified as "transformation toward sustainable development" (United Nations 2019).

Transformation is a never-ending process in food systems. Transition is the movement from one state to another. And evolution is the process of change. These are not interchangeable terminologies. Most food systems need all three.

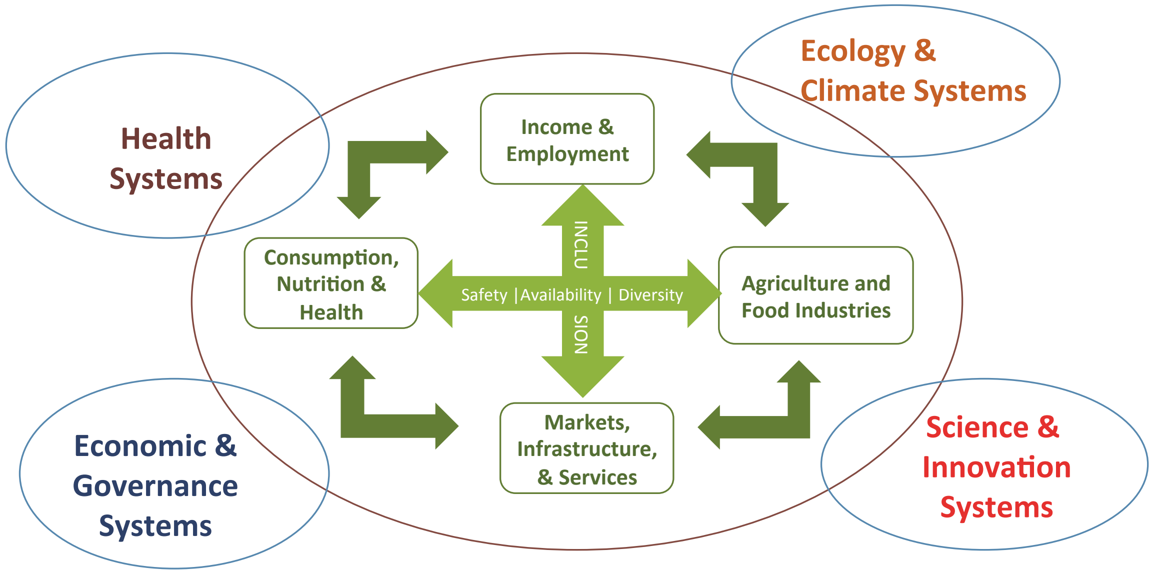
Concept of Food Systems

Conceptualising food systems entails defining systems boundaries and systems building blocks and linkages among them, while simultaneously being connected to neighbouring systems such as health, ecological, economy and governance, and the science and innovation systems (see figure 1). The concept here is in support of developing sustainable food and nutrition systems, to deliver health and well-being, embedded in the transformation towards a sustainable circular bio-economy.[3] Science and R&D play a role within each element and in the intersections among them for the food systems performance, and the science and innovation system impacts the functioning of system as a whole.

Food systems are in a continuous state of change and adaptation. For the Food Systems Summit this means an encouragement to raise the question of which policies, innovations, and institutions are needed to enhance positive side-effects or remediate or mitigate negative side-effects of policies, programmes, and other activities within or those that hold relevance to food systems transformation. These are inherent to the fact that agriculture, food processing, etc. always use energy, taking nutrients from the land and water to convert them into food, while simultaneously generating a significant level of greenhouse gas emissions in the process of production, which is further augmented if food is wasted. Therefore, a sustainable circular economy concept as an overarching systems frame, in which food systems are embedded, should be considered in the solution-finding process.

3 On the concept of sustainable circular bioeconomy see the communique of the Global Bioeconomy Summit 2020 https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf

Figure 1 The food system in the context of other systems (positive systems concept)



Source: Adapted from InterAcademy Partnership (2018) and von Braun (2017).

Further food systems components and drivers need mentioning, but are not depicted in figure 1. For instance, the system may be impacted by external shocks, such as climate, health or economic shocks. Moreover, wars and violent conflict increasingly disrupt food systems. Macro-policies such as fiscal (tax and expenditure), monetary, financial, and trade policies may promote or hamper food systems. Therefore, food systems concepts must consider the political and economic forces of their disruptions, and they need a political economy perspective (Pinstrup-Andersen and Watson 2011).

3. A FOOD SYSTEMS CONCEPT FOR THE UN FOOD SYSTEMS SUMMIT

Positive and Normative Food Systems Concept

Any action proposals emerging from the Food Systems Summit need to consider the great diversity of institutional arrangements and organizational structures in food systems. The respective actors and their values in a particular context also need to be considered. The food system is largely structured by private sector actors, including farmers, food manufacturers, traders, retailers, or food service businesses. At the same time, there are important features of cooperative and collective action arrangements among farming communities, like group formations by gender, regarding rural savings and banking, etc. Furthermore, there are industry clusters at large scales.

As mentioned earlier, systems can be conceptualised from a positive or from a normative perspective. The former concept, depicted in the previous section, attempts to design systems' structures and functions as they occur in the current real world as the basis on which a positive concept then identifies points of entry for desirable systems' change. The normative concept postulates a set of objectives and aims to shape the systems to serve the stated objectives. Both concepts aggregate and simplify real world structures and processes. Neither of these approaches escape the yardsticks of scientific evidence. For theoretical clarity of underlying value judgements, however, the two approaches need to be distinguished. As the Food Systems Summit is based on clearly stated objectives already defined in the SDGs, a normative approach is justified. Nonetheless, normative approaches need to be put to the test by positive approaches in order not to steer into a dead end of unrealistic wishful thinking. Thus, normative and positive approaches are complementary.

Action Tracks in the Food System

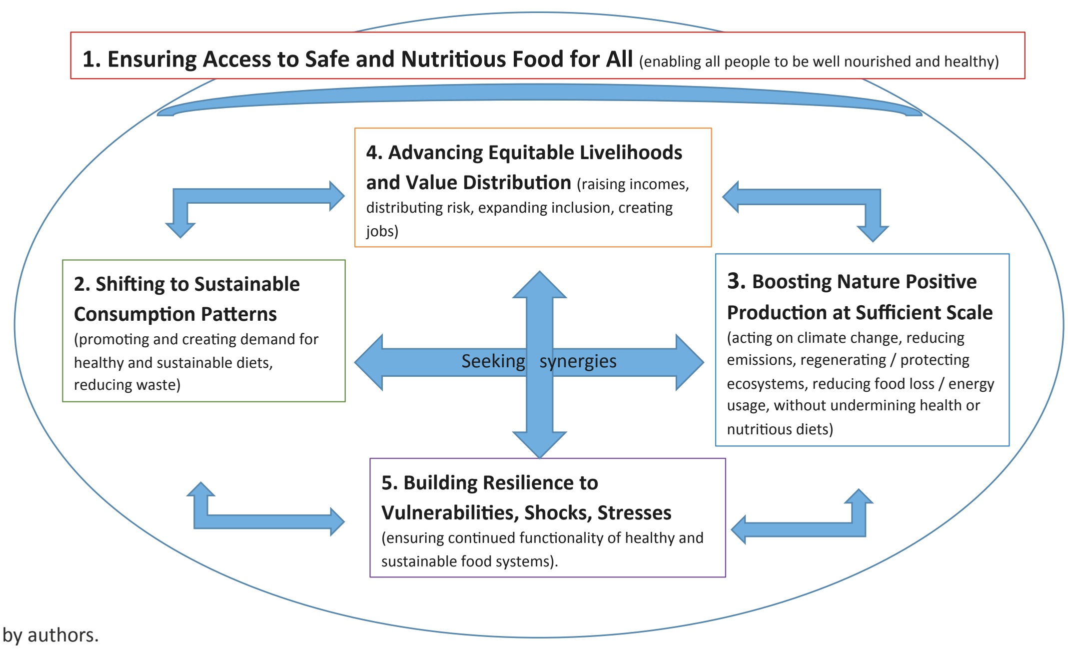
A normative concept and definition of food systems based on objectives embraces the five Actions Tracks listed below. Like any normative approach that states objectives, it is based on value judgements. Science needs to be transparent about value judgements. Normative definitions of sustainable and healthy food systems can be organised around intentional objectives. Areas of attention for policy and programme action and for building models of food systems that are aligned with the intentions as expressed in the 2030 Agenda can be facilitated. To build upon existing efforts, we suggest a concept of food systems that may help to frame action-oriented agenda setting, such as the one reflected in the five Action Tracks for the Food Systems Summit in support of the SDGs. These Action Tracks are described as:

1. ensuring access to safe and nutritious food for all (enabling all people to be well-nourished and healthy);
2. shifting to sustainable consumption patterns (promoting and creating demand for healthy and sustainable diets, reducing waste);
3. boosting nature-positive production at a sufficient scale (acting on climate change, reducing emissions and increasing carbon capture, regenerating and protecting critical ecosystems and reducing food loss and energy usage, without undermining health or nutritious diets);
4. advancing equitable livelihoods and value distribution (raising incomes, distributing risk, expanding inclusion, creating jobs); and
5. building resilience to vulnerabilities, shocks and stresses (ensuring the continued functionality of healthy and sustainable food systems).

We note that some elements of the headings of the Action Tracks, such as "nature positive", imply a narrative that may be surprising and new, not rooted in the established research literature or in terminology of SDGs. We do not further elaborate the details of the Action Tracks here, as this is done detailed background papers.[4] Nonetheless, if food systems shall deliver on the stated objectives (i.e. the SDGs), the Food Systems Summit needs to be open to new thinking, new concepts, and establishing new institutional and organizational arrangements. Addressing symptoms of systems failures will not be sufficient.

The five Action Tracks capture various key opportunities and challenges of food systems and relate to one or more food systems components, but they do not define a food systems concept as such. Therefore, the pursuit of the Action Tracks needs to be conscious of an overarching food systems concept. Pursuing each Action Track in isolation from the others would lead to inefficient solution proposals that neglect system-wide effects. The Tracks should better be understood as interlinked Action Areas. We thus offer an approach that attempts to position the five Action Tracks in a food systems framework (Figure 2). All of the Action Tracks have their strong justification and they are not in a hierarchical relationship: we expect food security and nutrition, livelihood improvements, and production with environmental sustainability, we want resilience to shocks (i.e. low variability, and a quick recovery from negative shocks), and we know

Figure 2 Action Tracks in a food system (a normative systems perspective)



Source: Designed by authors.

4 The background papers on Action Tracks by the Scientific Group are available at https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/ .

that consumption patterns are a powerful lever for change. "Ensuring Access to Safe and Nutritious Food for All (enabling all people to be well-nourished and healthy)" is supported by the other four Action Tracks, yet there are also feedbacks from improved nutrition to the other four Action Tracks. The Action Tracks need to consider functional relationships among them in systemic ways.

Cross-cutting Systems Issues

The systems perspective must not overlook some key cross-cutting issues and themes, which need due attention, for example:

- Covid-19 has brought to the fore the intertwining of food and health systems, and going forward more attention will need to be paid on how to make food systems more resilient to health shocks and pandemics, just as more attention is now being paid to how to make food systems more resilient to weather and climate shocks.
- The important role of science and new and emerging technologies and innovations in improving productivity, efficiency, equity, and sustainability of food systems, including digitisation, big data, Internet of Things, drones and Artificial Intelligence.[5]
- The role of women and gender are very important determinants for productive, healthy and sustainable food systems. Women's empowerment positively affects all five Action Tracks.
- Besides gender inequalities, overall inequalities across classes, regions, rural-urban contexts, and social groups also influence whether food systems will transform to be healthier, more sustainable, and more equitable. Some food systems can be inequal or can breed inequalities through land and other asset ownership and market power relationships. The situation of the youth as well as of the elderly deserve particular attention.
- The inclusive transformation of smallholders will be imperative. Smallholders are not a homogenous group, and transformation of the small farm economy around the world will call for different policies to address the heterogeneity of smallholders, and attention to the long-term nature of farming decisions.
- Lessons from indigenous food systems and related knowledge need to be systematically collected and considered for putting to work at scale, and they can also benefit from innovations and adaptations to changing circumstances.
- Strengthening sustainable food systems in marginalised areas and for marginalised communities will require the humanitarian and development communities to work more closely together in food systems transformation. The concept of rights based approaches need particular attention in these contexts.
- Trade, market structures and dynamics of food industries require policy attention. Appropriate anti-trust regulations need to address excessive concentrations. Intellectual property and food quality standards need transparent rules to incentivise the potential of food industries to contribute to healthy diets at affordable costs. Food industries' science capacities might be incentivised to serve public good innovations.
- There is a tendency to think of food systems as terrestrial systems only. It will be vital to broaden the understanding of food systems to include oceans / blue economy more fully given the tremendous current and potential future importance of fish and seafood to help assure healthy diets and address serious challenges in the management and exploitation of water-related natural resources, and the livelihoods of fishing and coastal communities (Costello et al. 2019).

These are a few of the cross-cutting issues and themes that need attention in food systems transformation. These and more cross-cutting areas of action for attention by the Food Systems Summit are being addressed in briefing papers from partners of the Scientific Group.[6]

As stressed above, food systems are multi-dimensional and cut across many different sectors. Convergence of policies and actions will be needed at national and global levels of agriculture, health, water, sanitation, women and child welfare, and so forth to achieve healthy, sustainable, and equitable food systems. Understanding cross-cutting issues require innovative quantitative modelling. Structural and change-related data are essential for analysing and modelling impacts of policies on food systems. There are tremendous opportunities for new data sources from remote-sensing, web-based, and cell-phone based data sources connecting to people who can facilitate new insights

5 Concerns need attention about a digital divide in access to these data as well as about the economic and social benefits of big data platforms that are able to amass extraordinary amounts of information on consumer behaviour and preferences.

6 See the list of published Briefs in Annex 1 of this volume

into food systems functions. Access and ownership matters related to these data need policy attention.

Considering Culture and Values

Food systems are closely related to people's values and cultures. Society demands from government and industry to make sure that food systems can be trusted. Considering and respecting people's values and their differences is therefore important for the Food Systems Summit to facilitate agreements on actions. Nonetheless, differences do exist even around broad societal issues with relevance to food systems. For instance, this is demonstrated by findings from the World Values Survey, a large-scale project to quantify cross-country differences and trends over time in people's values and attitudes (Inglehart et al. 2014). The 2011-14 World Values Survey asked respondents whether they think protecting the environment should be the priority, or whether economic growth and jobs should be prioritised. Interestingly, there is only a weak correlation between countries' overall level of economic development and the share of respondents prioritising economic growth over protecting the environment. Moreover, even in countries with a clear preference for either option, there is typically a large minority choosing the other option, while a national consensus is rare. This hints at the challenges of finding consensus among and within countries on food systems actions. Furthermore, values may change in the face of new technologies and advanced communication opportunities.

Change will not be achieved without respecting ethics and norms that govern food systems' operations. The discourse on food systems must not abstract from the issue of culture and values, making it seem as if it is merely a technical question. This especially – but not only – applies to the greatly diverse indigenous food systems, and the culture and knowledge embedded in them. Different societies may make different choices, based on their cultural traditions and local circumstances. For transformative policy approaches to be acceptable they will need to take into account values and cultural traditions.

Main Objectives

Linear hierarchical thinking would not do justice to food systems. The Action Tracks need a systems frame that defines sustainable food systems that deliver health and nutrition within the scope of the following three objectives:

Objective 1: End hunger and achieve healthy diets for all. Sustainable food systems must provide food and nutrition for all people. It is well-known that a focus only on promoting yield increases, calorie consumption, and low food prices is insufficient. Calorie consumption alone does not constitute a healthy diet. While it is difficult to define a high-quality, healthy diet in universal terms (Neufeld, Hendricks, and Hugas 2021), all assessments clearly indicate that healthy diets are more diverse and expensive than energy- and nutrient-adequate diets (FAO 2020; Hirvonen et al. 2019). While efforts need to be made to make healthy food accessible and affordable, it should be noted that lower food prices can hurt producers and discourage them from investing in technologies to protect the ecosystem, especially if ecosystem services related to food systems are not incentivised. It is important to understand the interactions between diets, health systems, and food systems to make progress towards the SDGs and their related targets in agriculture, inequality, poverty, sustainable production, consumption, nutrition, and health.

Objective 2: Achieving Objective 1 does not automatically enable the **sustainable use of biodiversity and natural resources, the protection of ecosystems and the safeguarding of land, oceans, forests, freshwater, and climate**, all of which are essential for protecting life in all its forms and which are a precondition for achieving social justice and robust, sustained economic development. Food systems operations to boost sustainable production must be compatible with ecosystem services. Nonetheless, actions to promote the sustainable use of natural resources and mitigate the effects of climate change can limit current agricultural productivity. Sustainable food systems need to find ways to address this trade-off. Agro-ecological- and agro-forestry farming practices can be steps in this direction, along with innovations such as edible insect farming, vertical agriculture, and so forth. Like all systems innovations their performance needs to stand the test of evidence.

Objective 3: Eliminate poverty and increase income and wealth. Poverty and hunger are interlinked and reducing extreme poverty directly impacts the elimination of hunger and all forms of malnutrition. Eliminating poverty alone does not make healthy diets affordable for everyone. Moreover, the elimination of poverty is difficult to achieve while also protecting the environment and preserving ecosystems. Changing food systems need to ensure that people with a low income can access a healthy diet by enabling them to earn living wages.

In addition to these objectives, further criteria need to remain in perspective as they are linked to broader objectives of the 2030 Agenda. They include the aforementioned cross-cutting themes, as well as the reduction of risks and the fostering of **food systems' resilience**,[7] and – importantly – also embrace respect for cultural principles and food traditions (Béné et al. 2019).

4. CONCLUDING REMARKS

Food systems transformation has to have a perspective on where we want to be headed. We then need to understand what is entailed in the transition to desirable food systems, and how to facilitate the evolution of such food systems. Thus, a vision for food systems transformation is required, and pursued with a strong sense of urgency. The vision is based on the SDGs. Nonetheless, the time horizons of the food systems transformations need to reach far beyond 2030, given demographic change, climate change, technological change and people-nature linkages in the Anthropocene.

The purpose of this paper was to define and clarify concepts of food systems, and thereby facilitate more meaningful discourses and dialogues for the agenda setting processes towards the Food Systems Summit. The paper is not an agenda setting paper. The ambitious agenda of the Food Systems Summit is actually defined by the SDGs, and in particular the SDG No.2. The five Action Tracks are means to focus action and implementation. We provided a framework to emphasise their inter-connections as well as their linkages to the key goals.

The Food Systems Summit UN leadership has called upon the science communities of the world to constructively engage for achieving an action-oriented Summit that is evidence based. The broad-based science community is responding to that call. Science offers insights to accelerate the transformation to desirable food systems. Investing in science, i.e. research, scientific data, tools and capacity, is essential to innovate, develop, and implement game-changing propositions that fit the respective food systems contexts.

The Summit needs to address systems failures that have contributed to the hunger, malnutrition, and obesity problems, the environmental problems of deforestation, greenhouse gas emissions, biodiversity losses and species extinctions, the problems of poor livelihoods in farming communities especially of women and youth, and the fundamental issues of food system-related violations of rights, broadly defined as the human right to food.

The Food Systems Summit needs to offer propositions to address these failures and accelerate the transformation of food systems, and this is where science-based innovations come in; for instance, innovations in policies for reducing the cost of healthy diets, innovations of institutions, innovations in technologies for plant breeding, animal health, new protein production, innovations in using digital opportunities, and many more.

Science and policy have a lot to gain from cooperation, but the independence of science must not be compromised to, for example, counter conventional wisdom or address policy and institutional failures with evidence-based insights. Science that produces new insights and technologies also needs to constantly seek the trust of society.

7 Food systems need to continue to function under risks and when coping with shocks and crises. This concerns regions that are experiencing conflict, climatic changes and natural disasters and is also globally the case, as food systems need to mitigate the impact of global crises, such as a pandemic, to protect food and nutrition security of people at all levels of development.

REFERENCES AND SELECTED BIBLIOGRAPHY ON FOOD SYSTEMS

1. Barrett, Christopher B., Tim Benton, Jessica Fanzo, Mario Herrero, Rebecca J. Nelson, Elizabeth Bageant, Edward Buckler, Karen Cooper, Isabella Culotta, Shenggen Fan, Rikin Gandhi, Steven James, Mark Kahn, Laté Lawson-Lartego, Jiali Liu, Quinn Marshall, Daniel Mason-D'Croz, Alexander Mathys, Cynthia Mathys, Veronica Mazariegos-Anastassiou, Alesha (Black) Miller, Kamakhya Misra, Andrew G. Mude, Jianbo Shen, Lindiwe Majele Sibanda, Claire Song, Roy Steiner, Philip Thornton, and Stephen Wood (2020). Socio-technical Innovation Bundles for Agri-food Systems Transformation, Report of the International Expert Panel on Innovations to Build Sustainable, Equitable, Inclusive Food Value Chains. Ithaca, NY, and London: Cornell Atkinson Center for Sustainability and Springer Nature, 2020. https://www.nature.com/documents/Bundles_agrifood_transformation.pdf
2. Béné, C., Oosterveer, P., Lamott, L., Brouwer, I.D., de Haan, S., & Prager, S.D. 2019. When food systems meet sustainability – Current narratives and implications for actions. World Development, 113 (2019): 116–130. https://doi.org/10.1016/j.worlddev.2018.08.011.
3. Burlingame, B. & Dernini, S. (eds). 2012. Sustainable Diets and Biodiversity. Directions and Solutions for Policy, Research and Action. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Available at: http://www.fao.org/3/i3004e/i3004e00.htm. (Accessed December 16, 2020).
4. Costello, C., L. Cao, S. Gelcich et al. 2019. The Future of Food from the Sea. Washington, DC: World Resources Institute. Available online at www.oceanpanel.org/future-food-sea
5. CFS (Committee on World Food Security). 2012. Coming to Terms with Terminology: Food Security, Nutrition Security, Food Security and Nutrition, Food and Nutrition Security. 39th Session, Rome, October 15-20, 2012. Available at: http://www.fao.org/docrep/meeting/026/MD776E.pdf. (Accessed December 16, 2020).
6. Dubé, L., Webb, P., Arora, N.K., & Pingali, P. 2014. Agriculture, Health, and Wealth Convergence: Bridging Traditional Food Systems and Modern Agribusiness Solutions. Annals of the New York Academy of Sciences, 1331 (1): 1-14. http://doi.wiley.com/10.1111/nyas.12602.
7. FAO (Food and Agriculture Organization of the United Nations). 2014. Sustainable food value chain development: guiding principles. FAO, Rome, Italy. Available at: http://www.fao.org/sustainable-food-value-chains/library/details/en/c/265156/. (Accessed December 16, 2020).
8. FAO. 2018. Sustainable food systems: concept and framework. Brief. FAO, Rome, Italy. Available at: http://www.fao.org/3/ca2079en/CA2079EN.pdf. (Accessed December 16, 2020).
9. FAO. 2020. A Framework for Promoting Food Systems Transformation Aligned to the 2030 Agenda and the Sustainable Development Goals. FAO, Rome, Italy.
10. FAO, IFAD, and WFP (Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, and World Food Programme). 2020. (and various years) The State of Food Insecurity in the World. FAO, Rome, Italy.
11. Fan, Shenggen, R. Pandya-Lorch, S. Yosef, Eds. 2014. Resilience for food and nutrition security. Washington, DC: IFPRI.
12. Food and Land Use Coalition. 2019. Growing Better: Ten Critical Transitions to Transform Food and Land Use.
13. Gallón, L. 2019. Systemic Thinking. In: Leal Filho, W., Azul, A., Brandli, L., Özuyar, P. & Wall, T. (eds). Quality Education Encyclopedia of the UN Sustainable Development Goals. Springer, Berlin, Germany. https://doi.org/10.1007/978-3-319-69902-8_58-1.
14. Global Panel on Agriculture and Food Systems for Nutrition. 2020. Future Food Systems: For people, our planet and prosperity. London 2020. https://www.glopan.org/foresight2/
15. Gupta, A. (2016). Grass Roots Innovation. Penguin Random House, India Gurgaon.
16. Gustafson, D., Gutman, A., Leet, W., Drewnowski, A., Fanzo, J., & Ingram, J. 2016. Seven Food System Metrics of Sustainable Nutrition Security. Sustainability, 8(3): 191. https://doi.org/10.3390/su8030196.
17. Haddad, L., Hawkes, C., Waage, J., Webb, P., Godfray, C. and Toulmin, C. 2016. Food systems and diets: Facing the challenges of the 21st century. London, UK: Global Panel on Agriculture and Food Systems for Nutrition.
18. Herrero, Mario, Philip K. Thornton, Daniel Mason-D'Croz, Jeda Palmer, Tim G. Benton, Benjamin L. Bodirsky, Jessica R. Bogard , Andrew Hall, Bernice Lee, Karine Nyborg, Prajal Pradhan, Graham D. Bonnett, Brett A. Bryan, Bruce M. Campbell, Svend Christensen, Michael Clark, Mathew T. Cook, Imke J. M. de Boer, Chris Downs, Kanar Dizyee, Christian Folberth, Cecile M. Godde, James S. Gerber, Michael Grundy, Petr Havlik, Andrew Jarvis, Richard King, Ana Maria Loboguerrero, Mauricio A. Lopes, C. Lynne McIntyre, Rosamond Naylor, Javier Navarro, Michael Obersteiner, Alejandro Parodi ,

Mark B. Peoples, Ilje Pikaar, Alexander Popp, Johan Rockström, Michael J. Robertson, Pete Smith, Elke Stehfest, Steve M. Swain, Hugo Valin, Mark van Wijk, Hannah H. E. van Zanten, Sonja Vermeulen, Joost Vervoort and Paul C. West et al. (2020) Innovation can accelerate the transition towards a sustainable food system. Perspective nature food. https://doi.org/10.1038/s43016-020-0074-1,

19. HLPE (High-Level Panel of Experts on Food Security and Nutrition). 2013. Investing in smallholder agriculture for food security. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome, Italy. Available at: http://www.fao.org/family-farming/detail/en/c/273868/. (Accessed December 16, 2020).
20. HLPE. 2017. Nutrition and Food Systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee in World Food Security. Rome, Italy. Available at http://www.fao.org/3/a-i7846e.pdf). (Accessed June 9, 2020).
21. HLPE. 2020. Food security and nutrition: building a global narrative towards 2030. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome, Italy. Available at http://www.fao.org/3/ca9731en/ca9731en.pdf
22. Hölscher, K., Wittmayer, J.M., & Loorbach, D. 2018. Transition versus transformation: What's the difference? Environmental Innovation and Societal Transitions, 27: 1-3. https://doi.org/10.1016/j.eist.2017.10.007.
23. IFPRI (International Food Policy Research Institute). 2016. Global Nutrition Report - From Promise to Impact: Ending Malnutrition by 2030. IFPRI, Washington, DC. Available at: https://www.ifpri.org/publication/global-nutrition-report-2016-promise-impact-ending-malnutrition-2030. (Accessed December 16, 2020).
24. IFPRI. 2020. 2020 Global Food Policy Report: Building Inclusive Food Systems. Washington, DC: International Food Policy Research Institute. https://doi.org/10.2499/9780896293670
25. Inglehart, R., C. Haerpfer, A. Moreno, C. Welzel, K. Kizilova, J. Diez-Medrano, M. Lagos, P. Norris, E. Ponarin & B. Puranen et al. (eds.). 2014. World Values Survey: Round Six - Country-Pooled Datafile Version: http://www.worldvaluessurvey.org/WVSDocumentationWV6.jsp . Madrid: JD Systems Institute.
26. Ingram, J. 2011. A food systems approach to researching food security and its interactions with global environmental change. Food Security, 3(4): 417–431. https://doi.org/10.1007/s12571-011-0149-9.
27. IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2019. Global Assessment Report on Biodiversity and Ecosystem Services Available at: https://ipbes.net/global-assessment. (Accessed June 9, 2020).
28. IPCC. 2011. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
29. IPCC. 2019. Summary for Policymakers. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley (eds). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Geneva, Switzerland. Available at: https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf. (Accessed December 16, 2020).
30. InterAcademy Partnership. 2018. Opportunities for future research and innovation on food and nutrition security and agriculture: The InterAcademy Partnership's global perspective. Trieste and Washington, DC, Schaefer Druck und Verlag GmbH. Available at: https://www.interacademies.org/sites/default/files/publication/iap_fnsa_global_web_complete_28nov.pdf. (Accessed December 18, 2020).
31. Johnston, J.L., Fanzo, J.C., & Cogill, B. 2014. Understanding Sustainable Diets: A Descriptive Analysis of the Determinants and Processes That Influence Diets and Their Impact on Health, Food Security, and Environmental Sustainability. Advances in Nutrition, 5 (4): 418-29. https://doi.org/10.3945/an.113.005553.
32. Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A. et al. (2014): Increasing homogeneity in global food supplies and the implications for food security. Proceedings of the National Academy of Sciences of the United States of America, 111 (11): 4001-4006. https://doi.org/10.1073/pnas.1313490111.
33. Lutz, W. 2020. World Population Trends and the Rise of homo sapiens literata. In: Transformative Roles of Science in Society: From Emerging Basic Science Toward Solutions for People's Wellbeing. EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA • MMXX Edited by Joachim von Braun Marcelo Sánchez Sorondo. Pp 43-67.
34. Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W. 1972. The Limits to Growth. A Report

for the Club of Rome's Project on the Predicament of Mankind. New York, Universe Books.

35. Nesheim, M.C., Oria, M., & Yih, P.T. 2015. A framework for assessing effects of the food system. Committee on a Framework for Assessing the Health, Environmental, and Social Effects of the Food System; Food and Nutrition Board; Board on Agriculture and Natural Resources; Institute of Medicine; National Research Council. Washington, DC. The National Academies Press. Available at: http://www.nycfoodpolicy.org/wp-content/uploads/2014/05/A-Framework-for-Assessing-Effects-of-the-Food-System.pdf. (Accessed December 16, 2020).
36. Lynnette M Neufeld, Sheryl Hendriks, Marta Hugas. 2020. Healthy diet: A definition for the United Nations Food Systems Summit 2021. A paper from the Scientific Group for the UN Food Systems Summit. Draft for discussion. November 25th, 2020 https://sc-fss2021.org/
37. OECD (Organization for Economic Co-operation and Development). 2021. Making better policies for food systems. OECD Publishing. Paris.
38. Parsons, K., Hawkes, C. & Wells, R. 2019. Understanding the food system: Why it matters for food policy. Rethinking Food Policy: A Fresh Approach to Policy and Practice, Brief 2. Centre for Food Policy, City University of London. Available at: https://www.city.ac.uk/__data/assets/pdf_file/0008/471599/7643_Brief-2_What-is-the-food-system-A-food-policy-perspective_WEB_SP.pdf. (Accessed December 16, 2020).
39. Pinstrup-Andersen, Derrill D. Watson 2011.Food Policy for Developing Countries: The Role of Government in Global, National and Local Food Systems. Cornell University Press.
40. Pontifical Academy of Sciences and Global Alliance for Improved Nutrition (GAIN). 2018. Final Statement of the Workshop on Food Safety and Healthy Diets. The Vatican. Available at: http://www.pas.va/content/accademia/en/events/2018/food/statement.html. (Accessed December 16, 2020).
41. Popkin, B.M., Adair, L.S., & Ng, S.W. 2012. Global nutrition transition and the pandemic of obesity in developing countries. Nutrition reviews, 70(1): 3-21. https://doi.org/10.1111/j.1753-4887.2011.00456.x.
42. Radzicki, M.J. & Taylor, R.A. 2008. Origin of System Dynamics: Jay W. Forrester and the History of System Dynamics. In: U.S. Department of Energy's Introduction to System Dynamics.
43. SAM (European Commission's Scientific Advice Mechanism). 2019. A scoping review of major works relevant to scientific advice towards an EU sustainable food system. Scoping Review Report. Available at: http://ec.europa.eu/research/sam/pdf/meetings/hlg_sam_032019_scoping_report_sustainable-food.pdf. (Accessed December 16, 2020).
44. SAPEA (Science Advice for Policy by European Academies). 2020. A sustainable food system for the European Union. SAPEA, Berlin, Germany. https://doi.org/10.26356/sustainablefood.
45. Schulz, T.W. 1964. Transforming Traditional Agriculture. New Haven: Yale University Press.
46. Sen, A. 1982. Poverty and Famines. An Essay on Entitlement and Deprivation. Oxford: Clarendon Press.
47. Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H.C.J., Gollin, D., Rayner, M., Ballon, P., & Scarborough, P. 2016. Global and regional health effects of future food production under climate change: a modelling study. The Lancet, 387(10031): 1937-1946. https://doi.org/10.1016/S0140-6736(15)01156-3.
48. Tendall, D.M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q.B., Kruetli, P., Grant, M. & Six, J. 2015. Food System Resilience: Defining the Concept. Global Food Security, 6: 17-23. https://doi.org/10.1016/j.gfs.2015.08.001.
49. The Global Panel on Agriculture and Food Systems for Nutrition. 2020. Future Food Systems: For people, our planet and prosperity. London 2020. https://www.glopan.org/foresight2/
50. Tilman, D, and M. Clark. 2014. Global diets link environmental sustainability and human health. Nature. 515: 518-522
51. UNEP (United Nations Environment Programme). 2011. Towards a green economy: Pathways to sustainable development and poverty eradication. Nairobi, Kenya. Available at: https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=126&menu=35. (Accessed December 16, 2020).
52. UNEP. 2016. Food Systems and Natural Resources. A Report of the Working Group on Food Systems of the International Resource Panel. Available at: https://www.resourcepanel.org/reports/food-systems-and-natural-resources. (Accessed June 9, 2020).
53. United Nations. 2019. Global Sustainable Development Report 2019: The Future is Now – Science for Achieving Sustainable Development. United Nations, New York, USA. Available at: https://sustainabledevelopment.un.org/globalsdreport/2019. (Accessed December 16, 2020).
54. United Nations. 2020a. Sustainable Development Goals. New York, USA. Available at: https://sdgs.un.org/goals. (Accessed September 12, 2020).

55. United Nations. 2020b. Sustainable Development Goal 2. New York, USA. Available at: https://sdgs.un.org/goals/goal2. (Accessed September 12, 2020).
56. van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Pérez Domínquez, I., Bodirsky, B.L., van Dijk, M., Doelman, J., & T. Fellmann. 2018. Comparing impacts of climate change and mitigation on global agriculture by 2050. Environmental Research Letters, 13(064021). https://doi.org/10.1088/1748-9326/aabdc4.
57. Vermeulen SJ, Campbell BM, Ingram JSI. 2012. Climate change and food systems. Annual Review of Environment and Resources. 37: 195-222.
58. von Braun, Joachim, Bezawit Beyene Chichaibelu, Maximo Torero Cullen, David Laborde, Carin Smaller (2020). Ending Hunger by 2030 – policy actions and costs. A Policy Brief, October 12th, 2020. Berlin https://www.zef.de/fileadmin/downloads/SDG2_policybrief.pdf
59. von Braun, J. 2017. Agricultural change and health and nutrition in emerging economies. In Pingali, P. & Feder, G. (eds.), Agriculture and rural development in a globalizing world. Earthscan Food and Agriculture Series. London: Routledge.
60. WBGU (German Advisory Council on Global Change). 2011. World in transition: A social contract for sustainability. Berlin, Germany. Available at: https://www.wbgu.de/en/publications/publication/world-in-transition-a-social-contract-for-sustainability. (Accessed December 16, 2020).
61. Welthungerhilfe and Concern International. 2020. Global Hunger Index. Bonn and Dublin. Available at: https://www.globalhungerindex.org/download/all.html. (Accessed December 16, 2020).
62. Wheeler, T. & von Braun, J. 2013. Climate change impacts on global food security. Science, 341(6145): 508-513. https://doi.org/10.1126/science.1239402.
63. WHO (World Health Organization). 2013. Research Priorities for the Environment, Agriculture and Infectious Diseases of Poverty. Technical Report of the TDR Thematic Reference Group on Environment, Agriculture and Infectious Diseases of Poverty. WHO, Geneva, Switzerland. Available at: http://apps.who.int/iris/bitstream/10665/78129/1/WHO_TRS_976_eng.pdf. (Accessed December 16, 2020).
64. Willett, Walter, Johan Rockström, Brent Loken, Marco Springmann, Prof Tim Lang, Sonja Vermeulen, Tara Garnett, David Tilman, Fabrice DeClerck, Amanda Wood, Malin Jonell, Michael Clark, Line J Gordon, Jessica Fanzo, Corinna Hawkes, Rami Zurayk, Juan A Rivera, Wim De Vries, Lindiwe Majele Sibanda, Ashkan Afshin, Abhishek Chaudhary, Mario Herrero, Rina Agustina, Francesco Branca, Anna Lartey, Shenggen Fan, Beatrice Crona, Elizabeth Fox, Victoria Bignet, Max Troell, Therese Lindahl, Sudhvir Singh, Sarah E Cornell, K Srinath Reddy, Sunita Narain, Sania Nishtar, Christopher J L Murray. 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet Commissions. VOLUME 393, ISSUE 10170, P447-492. DOI:https://doi.org/10.1016/S0140-6736(18)31788-4.
65. World Bank. 2007. World development report 2008: Agriculture for development. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/5990. (Accessed December 16, 2020).

This Report was prepared by members of the Scientific Group.

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

HEALTHY DIET: A DEFINITION FOR THE UNITED NATIONS FOOD SYSTEMS SUMMIT

by Lynnette M Neufeld, Sheryl Hendriks, Marta Hugas

AIM OF THIS DOCUMENT:

The aim of this document is to propose a definition of healthy diets and related evidence, thus permitting the alignment of terminology for the Food Systems Summit.

Diets are combinations of foods and beverages (referred to as foods hereafter for simplicity) consumed by individuals. However, the specific combination of foods that make up healthy diets is context-specific and depends on many cultural, economic, and other factors. In this document, we provide a definition and overview of approaches that have been used to translate this into food-based recommendations. We also provide a brief review to highlight evidence, gaps and controversies related to defining healthy diets. The evidence for potential solutions to making healthy diets more available, affordable, and their production environmentally sustainable is the subject of much literature[1,2,3,4,5], the Action Track and Science Group papers, and is not discussed here.

ABOUT THE AUTHORS

Lynnette M. Neufeld (Canada) incoming President of the International Union of Nutrition Scientists (IUNS), Director Knowledge Leadership, Global Alliance for Improved Nutrition (GAIN).

Sheryl L. Hendriks (South Africa) Professor of Food Security & Director, Institute for Food, Nutrition and Well-Being, University of Pretoria.

Marta Hugas (Spain) Chief Scientist at European Food Safety Authority (EFSA).

DEFINITION:

A healthy diet is health-promoting and disease-preventing. It provides adequacy without excess, of nutrients and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances.

APPROACHES TO TRANSLATING HEALTHY DIET INTO SPECIFIC FOOD-BASED RECOMMENDATIONS:

Moving beyond the available broad definitions to operationalizing what constitutes a healthy diet has been the source of debate in the nutrition community for decades. Innumerable definitions exist, with many similarities and several contradictions emerging over time[6]. In part, the contradictions arise from diversity in the underlying health issues that the diets were intended to address. Approaches to operationalizing the broad definitions and a move to specific food-based recommendations have typically used one of three approaches: i) observing existing dietary patterns associated with a lower prevalence of specific diseases; ii) perspective approaches based on evidence related to one or several outcomes; and iii) indicative approaches providing evidence-based guidance to be adapted to a specific context. Several examples of each and their related strengths and weaknesses are discussed below.

1. Some research about healthy diets has observed dietary patterns in populations where certain diseases, usually non-communicable diseases (NCDs), appear less prevalent. Dietary patterns in these population groups are studied, then tested in other contexts for their potential to promote health or prevent disease. One well-known example is the Mediterranean diet[7], which has been the topic of much research[6]. There are several limitations to using such dietary patterns as the basis for recommendations, most importantly because they do not consider all potential health outcomes. These examples do not account for local availability and the affordability of food types or the cultural traditions and acceptablility of foods. Another approach has been to model optimal dietary patterns for a specific food group based on consumption and mortality data[8]. However, several challenges remain, including the lack of dietary data from many populations and sub-groups.
2. A second approach has been to quantify the specific dietary intake patterns associated with multiple outcomes, both human and environmental or planetary health. This dual outcome approach is not new. Principles to guide a "sustainable, healthy diet" based primarily on eating local and minimizing processed food were published as early as 1986[9]. From the start, these principles have received considerable criticism from the nutrition, agriculture, and food sectors[10]. The recent EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems[11] provided recommendations for the consumption of specific quantities of foods or groups of foods that promote human health and can be produced within planetary boundary considerations. As with earlier efforts, the EAT-Lancet Commission diet has received criticism on several fronts, including the lack of consideration of food affordability[12]. However, the Commission calls for research to adapt the diet to local contexts. Future studies may provide evidence of the potential to do so.
3. Finally, the World Health Organization (WHO) has identified a series of guiding principles for healthy diets that seek to address all forms of malnutrition and related health issues. Unlike the approaches above, this indicative approach is designed to permit the contextualization of recommendations to individual characteristics, cultural contexts, local foods and dietary customs[13]. Building on such evidence, food-based dietary guidelines (FBDG) are intended to guide the development and revision of national food and agricultural policies. FBDGs have been developed by over 100 countries[14]. The content of FBDG may vary by country or region but generally includes a set of recommendations for foods, food groups, and dietary patterns that minimize the risk of deficiencies, promote health, and prevent disease in specific contexts.

CONCLUSION:

This brief defines a healthy diet for the Food Systems Summit, placing human health promotion and disease prevention at the center. In doing so, we draw attention to food safety. Without ensuring safety, diets cannot nourish and instead will cause illness.

However, to inform policy and programmatic action, this definition must be translated into specific food-based recommendations. In doing so, the sustainability of food systems, food affordability, and cultural and other preferences must be considered. There will always be tensions between the indicative or guiding principles and approaches that propose more quantified recommendations. The former leaves much room for interpretation, while the latter tends to underestimate the complexities of extrapolating prescribed diets to varying age, sex, life stage, culture, food availability, or affordability, among other considerations.

The FAO and WHO have now set out a series of guiding principles to achieve contextually appropriate sustainable, affordable, healthy diets[15,16] that are aligned with the guiding principles for healthy diets (#3 above) and form the basis for such actions.

We hope that this overview can help to align terminology and concepts used in the Food Systems Summit concerning healthy diets and we encourage readers to read Annex 1 and 2 below for further information.

Annex 1: Defining nutritious foods

The distinction between diets and foods:
Over any particular period of time, an individual will eat many foods and combinations of foods. Diets are the combination of foods consumed over time, through which we achieve adequacy without excess of all nutrients (including energy). Foods that make up a healthy diet should be safe (see Annex 2) and nutritious. In this section, we will explore the concept of nutritious food, and related evidence, gaps and controversies.

A nutritious food is "one that provides beneficial nutrients (e.g., protein, vitamins, minerals, essential amino acids, essential fatty acids, dietary fibre) and minimizes potentially harmful elements (e.g. anti-nutrients, quantities of sodium, saturated fats, sugars)" (GAIN[17], drawing on definitions published by Drewnowski[18] and Katz et al.[19]). While conceptually simple, there is no straightforward, universally accepted approach to classifying individual foods as more or less nutritious. Similarly, some context specificity is required in the categorization of individual foods as nutritious. The same food, for example, whole fat milk, may provide much-needed energy and other nutrients to one population group (e.g., underweight three-year-old children), but be less "healthy" for another due to high energy (calories) and fat content (e.g., obese adults).

"Nutrient profiling" or the rating of foods based on their nutrient density (i.e., nutrient content per 100 g or per 100 kcal of energy or per serving) has evolved substantially in recent years as an approach to classifying individual foods as more or less nutritious[18,20]. Such scores now provide the basis for several regulatory and health-promoting efforts, including front of pack labeling and health claims[21]. Recent efforts have also proposed more complete profiling approaches that, in addition to nutrient density, take into consideration the food groups of ingredients (e.g., fruit or vegetable content), and further develop the content of ingredients (e.g., types of fat) that should be limited[20]. To date, nutrient profiling has been used predominantly for packaged foods in many high-income and several middle-income countries. Considerable limitations remain for extending its utility to unpackaged foods and in contexts where a large portion of food is not commercially produced.

Several evidence gaps and controversies that influence our ability to characterize health diets and nutritious foods:
While much progress has been made to characterize healthy diets, and classify individual foods as nutritious parts of healthy diets, several gaps in evidence and controversies remain.

- Imperfect characterization of population nutrient requirements to avoid deficiency and promote health: Reference values for nutrient intakes of humans have been established, focusing on the avoidance of deficiency and excess. Nutrient requirements vary by age, sex, and life stage (e.g., pregnancy), and among individuals such that no single nutrient requirement value can be defined, even within age/sex groups. Estimated average requirements are therefore developed and converted into recommended daily nutrient intake levels that will, at the population level, ensure that the requirements of 95% of the population are met[22]. Upper tolerable limits are set at the minimum level above which potential harmful effects may be observed and are essential for understanding health risks and avoiding excess. FAO[23] and many national governments have published nutrient requirements. However, several limitations exist, including diverse methodological approaches to setting estimated requirements, and the extrapolation of requirements from one age group to another, among others. Some experts are now calling for additional research to estimate requirements using a consistent approach[24].
  In addition to the focus on the positive (and negative) effects of individual nutrients, much research has focused on the potential health effects – both positive and negative – of consuming specific foods, food groups or dietary patterns[6]. This is critically important as it advances our understanding of the link between diet and health, and the importance of food, which contains many more bioactive components than just the commonly-known nutrients. Evidence of health-promoting qualities of bioactive components in many food groups (e.g., fruits and vegetables, nuts and seeds, fermented dairy) and the health-harming effects of excessive quantities of some nutrients or dietary components (e.g., trans fat, salt, sugar) forms the basis

of the guidelines proposed by FAO[15,25], WHO[13], and the High-Level Panel of Experts[16]. While the basic tenants of these guidelines are unlikely to change, evidence continues to evolve for all dietary components and to some extent is constrained by the imperfect estimates of nutrient requirements and tolerable upper limits discussed above. Some have also called for greater transparency and better management of commercial interests in researching the associations between food products and health outcomes[26]. Emerging evidence suggests that eventually dietary recommendations may be personalized to optimize human health outcomes based on individual characteristics[27,28], but science is still far from achieving this goal.

- Imperfect knowledge of the nutrient and "anti-nutrient" content of food: Our ability to fully characterize dietary patterns of populations and individuals (where data permit) is highly dependent on the quality of the food composition tables, i.e., databases containing the amounts of nutrients in foods per specific portion sizes. Unfortunately, there are many issues with food composition tables including a lack of data or out-of-date information for many countries and world regions, particularly for less common foods (e.g., edible insects), and substances that influence nutrient absorption (e.g., tannins, phytate), as well as lacking and/or out-of-date information on nutrients added (or lost) as a result of processing, including food fortification or plant breeding (biofortification), poor or unclear analytical approaches and the lack of consideration for nutrient bioavailability, among others[29]. Fortunately, this issue is well recognized and substantial advances have been made through the efforts of the INFOODS project of FAO[30].
- Lack of consensus and standardized definitions related to food processing and health implications: A growing body of evidence suggests that highly-processed foods (or ultra-processed foods) are human health-harming[31]. Recent studies have also highlighted the impact of such foods on the environment[32], an issue that was even raised in the early discussions on sustainable diets[9,10]. Recent studies have primarily used the NOVA classification of ultra-processed foods[33,34]. However, at present there is no single accepted definition that clearly lays out the specific aspects of food processing that may be health-harming[35,36]. The implications of highly-processed foods, particularly those high in sugar, trans fat and salt, are not under debate. Urgent consensus is needed on how to classify such foods, define food processing categories and operationalize the implications for the private sector.

Annex 2: Avoiding the consumption of health-harming substances

Bringing safety to the definition of healthy diets: Food safety refers to "all those hazards, whether chronic or acute, that may make food injurious to the health of the consumer"[37]. Food safety issues can arise from food contamination with biological hazards, pathogens, or chemicals (natural or processed contaminants, residues of pesticides or veterinary medicine etc.) during the production, processing, storage (including but not limited to the lack of adequate cold storage), transport and distribution of food, as well as in the household. Standards and controls are in place to protect consumers from unsafe foods[16,3]. In addition to the disease burden, food-borne disease in low- and middle-income countries (LMICs) is also a concern because of a broad range of economic costs and their impacts on market access[38].

Current knowledge suggests that biological hazards and antimicrobial resistance may present a higher disease burden than chemical hazards. However, there is still uncertainty due to difficulty in measuring and attributing long-term and chronic effects. Chronic effects due to chemicals (natural or processed contaminants, pesticide residues, etc.) are more challenging to trace and quantify their actual impact on disease burden. The study by the Foodborne Disease Burden Epidemiology Reference Group of the World Health Organization (FERG/WHO)[39] estimated that the global burden of food-borne diseases was comparable to that of HIV/AIDS, malaria and tuberculosis, with LMICs bearing 98% of this burden. The FERG/WHO report[39] quantified the burden of disease from the most critical food-borne toxins (aflatoxin, cassava cyanide and dioxins). Some work has also been done to estimate the burden of illness due to four food-borne metals (arsenic, cadmium, lead, methylmercury), which is estimated to be substantial[40]. As with nutrition, our evidence related to food safety and health continues to evolve. For example, the clinical outcome of exposure to food-borne pathogens may be modulated by the human gut microbiome[41].

Despite the heavy burden of disease among LMICs, the systems and practices for monitoring food-borne hazards and risks, food safety system performance and related disease outcomes are predominantly utilized in high-income countries (HICs). While there are many promising approaches to managing food safety in LMICs, few have demonstrated sustainable impact at scale. It is also essential to distinguish between food safety and food quality: food safety ensures that food is fit for human consumption and not harmful to human health and is most often under the competence of veterinary, health or agricultural inspectors, while food quality is a market category that is usually the responsibility of food or market inspectors[42].

Several evidence gaps and controversies that influence the ability to assess and ensure the safety of foods as part of a healthy diet:

- Food safety has complex interactions with other societal concerns. Safety must be built into foods, and this puts responsibility for food safety all along the value chain, including producers, processors, transporters, retailers, and consumers. If food chain actors lack the requisite knowledge, resources, and skills, then safety cannot be assured. Some food safety perceptions and knowledge may be shared generationally and may not be scientifically grounded. In many LMICs, food is often purchased from traditional markets close to the point of production and undergoes limited transformation[43]. Several traditional ways of processing food can be highly effective at reducing risk, but food-borne illness is may still be linked to poor hygiene conditions, close contact with animals, and limited access to clean water from the market through to the household. Informal market drivers and incentives for safe food are often weak, although adverse food safety events can leave the sellers vulnerable to reputational harm. As such, food safety has implications for livelihoods. Likewise, food-borne diseases can have important consequences for women's resilience. Women predominate in traditional food processing and sales and are usually responsible for food preparation at home.
- The preferred method for improving food safety and quality is preventive, and many but not all potential food hazards can be controlled along the food chain. Engaging the food industry at all levels to understand their role in preventing food contamination through the application of good practices, i.e., good agricultural practices (GAP), good manufacturing practices (GMP), good hygienic practices (GHP), and the Hazard Analysis Critical Control Point system (HACCP) is challenging. The HACCP principles have been formalized by the Codex Committee on Food Hygiene and provide a systematic structure that the food industry, both large and small, can use for identifying and controlling food-borne hazards. Governments should recognize the application of a HACCP approach by the food industry as a fundamental tool for improving the safety of food[37]. However, the level of safety that these food safety systems are expected to deliver has seldom been defined in quantitative terms.

  In addition to HACCP, the Codex Alimentarius Commission (CAC) sets standards to address the safety and nutritional quality of foods for most segments of the food chain to protect consumer health and fair practices. The CAC establishes standards for maximum levels of food additives, limits for contaminants and toxins, and residue limits for pesticides and veterinary drugs.
- Some countries, especially LMICs, have not adopted modern food safety control systems even though there is a significant burden of food-related illness[43]. Many countries lack effective public health surveillance systems, so the burden of food-borne disease and broader economic ramifications are not well understood. Food safety capacity may be concentrated either geographically, for example, in the capital city, or for niche markets intended for export. Building on these analyses, the World Bank recommends that governments consider how to make "smart" food safety investments, such as investing in foundational knowledge, human resources and infrastructure, including those that address basic environmental health issues, such as access to clean water, improved sanitation and reduced environmental contamination in the soil, water and air[43].

  Food safety priorities for countries include addressing risks from farm to table, changing from reactive to proactive approaches to food safety, and adopting a risk analysis approach to ensure prioritized decision-making. Building food safety capacity will assist governments in economic development by improving the health of their own citizens and opening countries to more food export markets and touris[43].

REFERENCES:

1. Herforth A. Cost and affordability of healthy diets across and within countries. Rome: FAO; 2020 p. 108.
2. Chaudhary A, Gustafson D, Mathys A. Multi-indicator sustainability assessment of global food systems. Nat Commun. Nature Publishing Group; 2018;9:1–13.
3. Smetana SM, Bornkessel S, Heinz V. A Path From Sustainable Nutrition to Nutritional Sustainability of Complex Food Systems. Front Nutr. 2019;6:39.
4. Badiane O, Makombe T. Beyond a middle income Africa: Transforming African economies for sustained growth with rising employment and incomes [Internet]. International Food Policy Research Institute (IFPRI); 2015 [cited 2020 Oct 25]. Available from: https://ebrary.ifpri.org/digital/collection/p15738coll2/id/130121
5. Program of Accompanying Research for Agricultural Innovation. From potentials to reality: Transforming Africa's food production (Investment and policy priorities for sufficient, nutritious and sustainable food supplies) [Internet]. Akedemiya and Center for Development Research Univeristy; 2020. Available from: https://www.researchgate.net/publication/344614700_From_potentials_to_reality_Transforming_Africa's_food_production_Investment_and_policy_priorities_for_sufficient_nutritious_and_sustainable_food_supplies
6. Cena H, Calder PC. Defining a Healthy Diet: Evidence for the Role of Contemporary Dietary Patterns in Health and Disease. Nutrients [Internet]. Multidisciplinary Digital Publishing Institute (MDPI); 2020 [cited 2020 Oct 13];12. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7071223/
7. Mocciaro G, Ziauddeen N, Godos J, Marranzano M, Chan M-Y, Ray S. Does a Mediterranean-type dietary pattern exert a cardio-protective effect outside the Mediterranean region? A review of current evidence. International Journal of Food Science and Nutrition. Taylor & Francis; 2017;69:524–35.
8. Afshin A, Sur PJ, Fay KA, Cornaby L, Ferrara G, Salama JS, Mullany EC, Abate KH, Abbafati C, Abebe Z, et al. Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet. 2019;393:1958–72.
9. Dye Gussow J, Clancy, Katherine L. Dietary Guidelines for Sustainability. Journal of Nutrition Education. 1986;18:1–5.
10. Dye Gussow J. Dietary Guidelines for Sustainability: Twelve Years Later. Journal of Nutrition Education. 1999;31:194–200.
11. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet. Lancet; 2019;393:447–92.
12. Hirvonen K, Bai Y, Headey D, Masters WA. Affordability of the EAT–Lancet reference diet: a global analysis. The Lancet Global Health. Elsevier; 2020;8:e59–66.
13. World Health Organization (WHO). Healthy diet [Internet]. Healthy diet. 2020 [cited 2020 Oct 25]. Available from: https://www.who.int/news-room/fact-sheets/detail/healthy-diet
14. Food and Agriculture Organization (FAO). Food Based Dietary Guidelines [Internet]. Food-Based Dietary Guidelines. [cited 2020 Oct 25]. Available from: http://www.fao.org/nutrition/education/food-dietary-guidelines/background/en/
15. Food and Agriculture Organization of the United Nations, World Health Organization. Sustainable healthy diets: guiding principles. 2019.
16. HLPE. Nutrition and Food Systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome; 2017. Report No.: 12.
17. Global Alliance for Improved Nutrition (GAIN). What constitutes a nutritious and safe food? [Internet]. Geneva, Switzerland: Global Alliance for Improved Nutrition (GAIN); 2017. Available from: https://www.gainhealth.org/sites/default/files/publications/documents/gain-nutritious-food-definition.pdf
18. Drewnowski A. Concept of a nutritious food: toward a nutrient density score. Am J Clin Nutr. Oxford Academic; 2005;82:721–32.
19. Katz DL, Doughty K, Njike V, Treu JA, Reynolds J, Walker J, Smith E, Katz C. A cost comparison of more and less nutritious food choices in US supermarkets. Public Health Nutrition. Cambridge University Press; 2011;14:1693–9.
20. Drewnowski A, Fulgoni VL, III. New Nutrient Rich Food Nutrient Density Models That Include Nutrients and MyPlate Food Groups. Frontiers in Nutrition [Internet]. Frontiers Media SA; 2020 [cited 2020 Oct 12];7. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7387572/
21. Croker H, Packer J, Russell SJ, Stansfield C, Viner RM. Front of pack nutritional labelling schemes: a systematic review and meta-analysis of recent

evidence relating to objectively measured consumption and purchasing. Journal of Human Nutrition and Dietetics. John Wiley & Sons, Ltd; 2020;33:518–37.
22. FAO, WHO. Human vitamin and mineral requirements [Internet]. 2002. Available from: http://www.fao.org/3/y2809e/y2809e00.htm#Contents
23. FAO. Nutrition requirements [Internet]. Food and Agriculture Organization of the United Nations. [cited 2021 Jan 18]. Available from: http://www.fao.org/nutrition/requirements/en/
24. Yaktine AL, King JC, Allen LH. Why the Derivation of Nutrient Reference Values Should be Harmonized and How It Can be Accomplished. Adv Nutr. Oxford Academic; 2020;11:1102–7.
25. Burlingame B. Sustainable diets and biodiversity - Directions and solutions for policy research and action Proceedings of the International Scientific Symposium Biodiversity and Sustainable Diets United Against Hunger. Rome: FAO; 2012.
26. Lesser LI, Ebbeling CB, Goozner M, Wypij D, Ludwig DS. Relationship between Funding Source and Conclusion among Nutrition-Related Scientific Articles. PLOS Medicine. Public Library of Science; 2007;4:e5.
27. Fenech M, El-Sohemy A, Cahill L, Ferguson LR, French T-AC, Tai ES, Milner J, Koh W-P, Xie L, Zucker M, et al. Nutrigenetics and Nutrigenomics: Viewpoints on the Current Status and Applications in Nutrition Research and Practice. J Nutrigenet Nutrigenomics. 2011;4:69–89.
28. Precision Nutrition—the Answer to “What to Eat to Stay Healthy”, JAMA [Internet]. DeepDyve. [cited 2020 Nov 22]. Available from: https://www.deepdyve.com/lp/american-medical-association/precision-nutrition-the-answer-to-what-to-eat-to-stay-healthy-sP0CivlA47
29. Micha R, Coates J, Leclercq C, Charrondiere UR, Mozaffarian D. Global Dietary Surveillance: Data Gaps and Challenges. Food Nutr Bull. 2018;39:175–205.
30. INFOODS: FAO/INFOODS Databases [Internet]. [cited 2020 Oct 26]. Available from: http://www.fao.org/infoods/infoods/tables-and-databases/faoinfoods-databases/en/
31. Hall KD, Ayuketah A, Brychta R, Cai H, Cassimatis T, Chen KY, Chung ST, Costa E, Courville A, Darcey V, et al. Ultra-Processed Diets Cause Excess Calorie Intake and Weight Gain: An Inpatient Randomized Controlled Trial of Ad Libitum Food Intake. Cell Metabolism. 2019;30:226.
32. Seferidi P, Scrinis G, Huybrechts I, Woods J, Vineis P, Millett C. The neglected environmental impacts of ultra-processed foods. The Lancet Planetary Health. Elsevier; 2020;4:e437–8.
33. Monteiro C, Cannon G, Levy R, Moubarac J, Louzada M, Rauber F, Khandpur N, Cediel G, Neri D, Martinez-Steele E, et al. Ultra-processed foods: what they are and how to identify them. Public Health Nutrition. Public Health Nutr; 2019;22:936–41.
34. Monteiro CA, Cannon G, Moubarac J-C, Levy RB, Louzada MLC, Jaime PC. The UN Decade of Nutrition, the NOVA food classification and the trouble with ultra-processing. Public Health Nutr. 2018;21:5–17.
35. Gibney M. Ultra-Processed Foods: Definitions and Policy Issues. Current Developments in Nutrition. Curr Dev Nutr; 2018;3:nzy077.
36. Gibney M, Forde C, Mullally D, Gibney E. Ultra-processed foods in human health: a critical appraisal. American Journal of Clinical Nutrition. Am J Clin Nutr; 2017;106:717–24.
37. Food and Agriculture Organization (FAO). Assuring food safety and quality: Guidelines for strengthening national food control systems [Internet]. Rome: FAO; 2003. Report No.: 76. Available from: http://www.fao.org/3/a-y8705e.pdf
38. Unnevehr L, Ronchi L. Food Safety Standards: Economic and Market Impacts in Developing Countries [Internet]. Washington, DC: The World Bank Group; 2014. Report No.: 341. Available from: http://documents1.worldbank.org/curated/en/681851471859603213/pdf/107910-VIEWPOINT-PUBLIC-TAG-TOPIC-investment-climate.pdf
39. Organization WH. WHO estimates of the global burden of foodborne diseases: foodborne disease burden epidemiology reference group 2007-2015 [Internet]. World Health Organization; 2015 [cited 2020 Oct 26]. Available from: https://apps.who.int/iris/handle/10665/199350
40. Gibb H, Barchowsky A, Bellinger D, Bolger P, Carrington C, Havelaar A, Oberoi S, Zang Y, O’Leary K, Devleesschauwer B. Estimates of the 2015 global and regional disease burden from four foodborne metals – arsenic, cadmium, lead and methylmercury. Environmental Research. Academic Press; 2019;174:188–94.
41. Josephs-Spaulding J, Beeler E, Singh OV. Human microbiome versus food-borne pathogens: friend or foe. Appl Microbiol Biotechnol. 2016;100:4845–63.
42. Independent Evaluation Group (IEG). The World Bank Group and the Global Food Crisis: An Evaluation of the World Bank Group Response [Internet]. Washington, DC: The World Bank; 2014. Available from: http://elibrary.worldbank.org/doi/book/10.1596/978-1-4648-0091-7

43. Jaffee S, Henson S, Unnevehr L, Grace D, Cassou E. The Safe Food Imperative: Accelerating Progress in Low- and Middle-Income Countries [Internet]. Washington, DC: The World Bank Group; 2019 p. 211. Available from: doi:10.1596/978-1-4648-1345-0

This Report was prepared by members of the Scientific Group.

UNITED NATIONS
FOOD SYSTEMS
SUMMIT 2021
The Scientific Group for the
UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

ENSURING ACCESS TO SAFE AND NUTRITIOUS FOOD FOR ALL THROUGH TRANSFORMATION OF FOOD SYSTEMS – A PAPER ON ACTION TRACK 1 –

by Sheryl Hendriks, Jean-François Soussana,
Martin Cole, Andrew Kambugu, David Zilberman

ABSTRACT

Action Track 1 of the Food Systems Summit offers an opportunity to bring together the crucial elements of food safety, nutrition, poverty and inequalities in the framework of food systems in the context of climate and environmental change to ensure that all people have access to a safe and nutritious diet. Achieving Action Track 1 goal is essential to achieving the goals of the other Action Tracks. With less than a decade left

ABOUT THE AUTHORS

Sheryl L. Hendriks (South Africa), Professor of Food Security & Director, Institute for Food, Nutrition and Well-being, University of Pretoria.

Jean-François Soussana (France), Vice-President of International Policy at the Institute national de la recherche agronomique (INRAE).

Martin Cole (Australia), Professor for Agriculture and Food within the Commonwealth Science and Industrial Research Organisation (CSIRO). Chairperson of the HLPE Steering Committee of CFS.

Andrew Kambugu (Uganda), Executive Director Infectious Diseases Institute (IDI), College of Health Sciences, Makerere University. Co-founder of the Researchers for Global Health (R4GH) initiative.

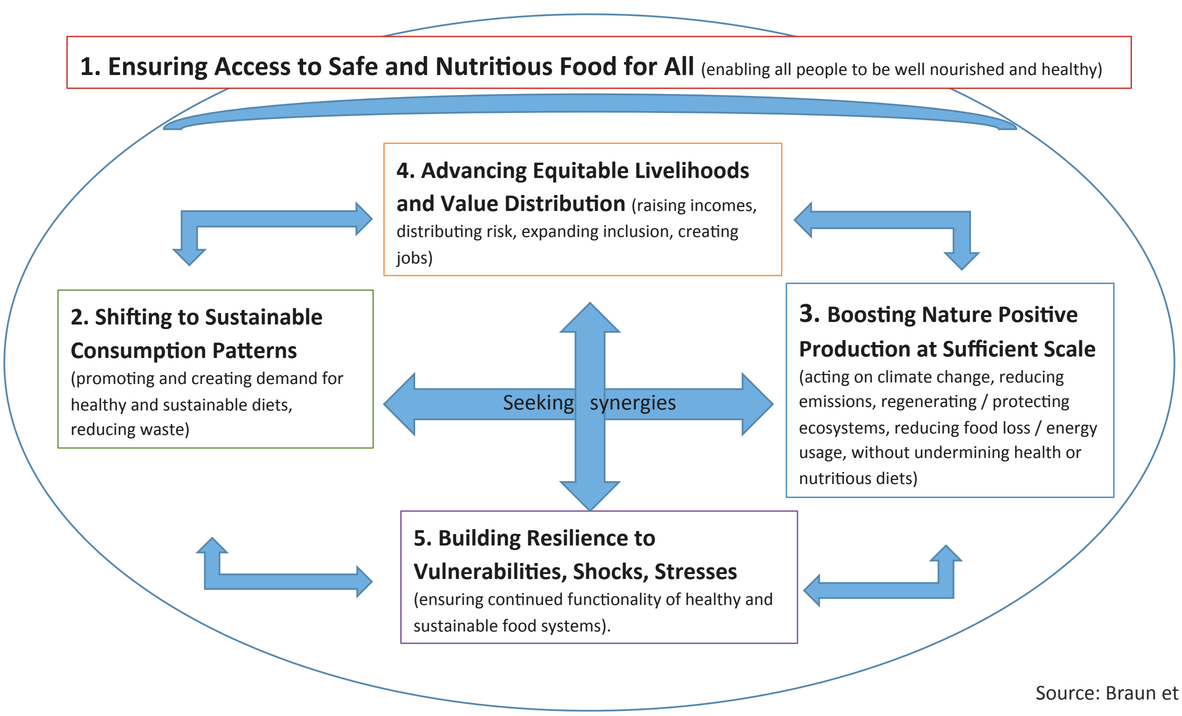
David Zilbermann (Israel, USA), Professor in the Department of Agricultural and Resource Economics, University of California at Berkeley. One of the Founders of the International Consortium of Applied Bio-economy Research (ICABR)

to achieve the Sustainable Development Goals (SDGs), most countries are not on target to achieve the World Health Organisation's nutrition targets and SDG 2 targets. The COVID-19 pandemic has exacerbated malnutrition and highlighted the need for food safety. The pandemic has also exposed the deep inequalities in society and food systems. Nonetheless, future food systems can address many of these failings and ensure safe and nutritious food for all. However, structural change is necessary to address the socio-economic drivers behind malnutrition, inequalities and the climate and environmental impacts of food. Adopting a whole-system approach in policy, research and monitoring and evaluation is crucial to manage trade-off and externalities from farm-level to national scales and across multiple sectors and agencies. Supply chain failures will need to be overcome and technology solutions adopted and adapted to specific contexts. A transformation of food systems requires coordinating changes in supply and demand in differentiated ways across world regions: bridging yield gaps and improving livestock feed conversion, largely through agro-ecological practices, deploying at scale soil carbon sequestration and greenhouse gas mitigation, reducing food losses and wastes, as well as over-nourishment and shifting the diets of wealthy populations. Global food systems sustainability also requires halting the expansion of agriculture into fragile ecosystems, while restoring degraded forests, fisheries, rangelands, peatlands and wetlands. Shifting to more sustainable consumption and production patterns within planetary boundaries will require efforts to influence food demand and diets, diversify food systems, careful land-use planning and management. Integrative policies need to ensure that food prices reflect real costs (including major externalities caused by climate change, land degradation and biodiversity loss, and public health impacts of malnutrition), reduce food waste and, at the same time, ensure safe and healthy food affordability, decent incomes and wages for farmers and food system workers. Harnessing science and technology solutions and sharing actionable knowledge with all players in the food system offers many opportunities. Greater coordination of food system stakeholders is crucial for greater inclusion, greater transparency and more accountability. Sharing lessons and experiences will foster adaptive learning and responsive actions. Careful consideration of the trade-offs, externalities and costs of not acting is needed to ensure that the changes we make benefit to all and especially the most vulnerable in society.

1. INTRODUCTION

Action Track 1 of the Food Systems Summit offers an opportunity to bring together the crucial elements of food safety, nutrition, poverty and inequalities in the framework of food systems in the context of climate and environmental change to ensure that all people have access to a safe and nutritious diet. These ele-

Figure 1 Action Tracks of the UN Food Systems Summit in a Normative Systems Perspective.



Source: Braun et al., 2021

ments are embedded in the fundamental human rights, including the right to food, the rights to safe water and sanitation (essential for safe food), as well as the right to be free from discrimination.

Food systems provide a framework to advance access to safe and nutritious food for all (including all crops, fish, forest foods and livestock). Food systems encompass all of the elements and activities that relate to the production, processing, distribution, preparation and consumption of food, as well as the output of these activities, including socio-economic and environmental outcomes (HLPE, 2020). Ensuring access to safe and nutritious food for all underlies the other Summit Action Tracks (Figure 1).

2. What is a safe and nutritious diet?

A safe and nutritious diet is a healthy diet that "is human health-promoting and disease-preventing. It provides adequacy (without an excess of nutrients) and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances" (Neufeld et al., 2021). A nutritious food "provides beneficial nutrients (e.g., protein, vitamins, minerals, essential amino acids, essential fatty acids, dietary fibre) and minimises potentially harmful elements (e.g. anti-nutrients, quantities of sodium, saturated fats, sugars)" (Neufeld et al. 2021, drawing on GAIN (2017), Drewnowski (2005) and Katz et al. (2011)). Safe food promotes health and is free of foodborne diseases caused by microorganisms, including bacteria, virus, prionics, parasites and chemicals, as well as foodborne zoonoses transferred from animals to humans and other associated risks in the food chain (WHO, 2013).

Malnutrition includes undernourishment, micronutrient deficiencies and overweight (including obesity). Malnutrition increases susceptibility to foodborne diseases, creating a vicious cycle for health, reducing productivity and compromising development. The COVID-19 pandemic is expected to increase the risk of all forms of malnutrition (Headey et al., 2020).

Recent reports draw attention to the affordability of a healthy diet (FAO, IFAD, UNICEF, WFP and WHO, 2020); Masters et al., 2018). The pandemic has exposed long-standing inequalities in our food and health systems that affect access to safe and nutritious food as well as income to enable this access (Laborde et al., 2020). Shocks (including health shocks such as COVID-19 that increase the need for a nutritious diet) make healthy diets less accessible and affordable.

While the definitions of an adequate diet and safe food are established and widely accepted, there is debate in the literature about what constitutes a sustainable diet. Each proposed diet has trade-offs in terms of affordability, climate and environmental impacts. These trade-offs are discussed in the sections that follow.

3. We are not on track to meet international targets for ensuring safe and nutritious food for all by 2030

Despite some progress in reducing the rate of extreme poverty, with only ten years to go to 2030, the world is not on track to meet nutrition-related targets. Table 1 presents a summary of the international targets related to ensuring safe and nutritious food for all. While the proportion of the population that is undernourished, stunting, low birth weight and anaemia among women of reproductive age have declined, the reductions are not sufficient to meet the global targets. The experience of food insecurity (FIES, a survey that comprises eight questions regarding people's access to adequate food) as measured by FAO et al. (2020) has increased somewhat. Moreover, the numbers of overweight children and adults is rising.

No country is exempt from the scourge of malnutrition. Undernutrition coexists with overweight, obesity and other diet-related non-communicable diseases (NCDs), even in poor countries. UNICEF et al. (2020) report that 37% of overweight children reside in low and middle-income countries. Likewise, fragile and extremely fragile countries are disproportionally burdened by high levels of all three forms of malnutrition compared to less-fragile countries (GNR, 2020).

While some progress has been made in certain countries and in some regions, the 2020 Global Nutrition report shows that no country is 'on course' to meet all of WHO's global nutrition targets (GNR, 2020). Although the health and behavioural actions required for reducing all forms of malnutrition are well documented (Lancet report, various WHO guidelines) as are the benefits (Hoddinott, etc.), progress is far too slow. Inequalities in society and the food system make affordable and healthy diets inaccessible to the most vulnerable populations. There is an urgent need to transform food systems to deliver on nutrition outcomes. Unless nutrition-specific (direct) and nutrition-sensitive (indirect) interventions are implemented at scale and in a sustainable way (see Box 1) with complementary services (such as regular deworming of children), the impact will be suboptimal (Ruel et al., 2018). In addition,

BOX 1: Sustainable food systems

"Sustainable food systems are: productive and prosperous (to ensure the availability of sufficient food); equitable and inclusive (to ensure access for all people to food and to livelihoods within that system); empowering and respectful (to ensure agency for all people and groups, including those who are most vulnerable and marginalized to make choices and exercise voice in shaping that system); resilient (to ensure stability in the face of shocks and crises); regenerative (to ensure sustainability in all its dimensions); and healthy and nutritious (to ensure nutrient uptake and utilization)" (HLPE, 2020).

urgent action is necessary to minimise the impact of the COVID-19 pandemic on children's nutrition (Ruel et al. 2020).

WFP has predicted that the number of people facing acute food insecurity in low and middle-income countries will nearly double to 265 million by the end of 2020 (WFP, 2020). Children are disproportionately affected, with likely intergenerational consequences for child growth and development. The pandemic's impact could have life-long implications for education, chronic disease risks and overall human capital formation (Martorell, 2017).

Approximately 600 million people fall ill through the consumption of contaminated food each year, with considerable differences among sub-regions; with the highest burden observed in Africa (WHO, 2020). More than 420 000 die every year, equating to the loss of 33 million Disability-Adjusted Life Years (WHO, 2015). Foodborne diseases disproportionately affect children, accounting for 40% of the foodborne disease burden. The consumption of unsafe foods cost low- and middle-income countries at least US$ 110 billion in lost productivity and medical expenses annually (Jaffee et al., 2019). With a large proportion of emerging human infectious diseases originating from animal sources (zoonotic diseases), there is also an increasing need to consider both animal and human health as a 'One Health' issue.

Devleesschauwer et al. (2018) report that food safety is a marginalised policy objective, especially in developing countries. The scale of foodborne outbreaks has become more extensive and has affected more countries since 2004 (INFOSAN, 2019), representing a constant threat to public health and an impediment to socio-economic development. However, updated data is not available regarding progress on reducing the incidence of foodborne diseases, presenting a major obstacle to adequately addressing food safety concerns (Devleesschauwer et al., 2017).

A recent innovation is the assessment of the adequacy, affordability and access to healthy diets included in the 2020 SOFI report (see affordability, Table 1). If continually updated, this indicator could become a comprehensive proxy for monitoring progress on ensuring safe, nutritious food for all.

Table 1 Taking stock

	Element	International target/s	Baseline year	Baseline estimate	Latest assessment year	Latest global estimates (with population estimates where available)	Change to date (global)
Nutrition	Hunger (Proportion of the population that is undernourished, PoU)[1]	SDG2: By 2030, end hunger and ensure access by all people, in particular, the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2004-2006	12.5% (FAO et al., 2020)	2017-2019	PoU = 8.8% (690 Million) (FAO et al., 2020)	Down 3.7%
	Prevalence of food insecurity (Food Insecurity Experience Scale, FIES) measured as the number of people living in households where at least one adult has been found to be food insecure (FAO et al., 2020)[1,2,3]		2014-2016	Severe – 8.1% Moderate – 22.7% (FAO et al., 2020)	2017-2019	Moderate FIES = 25% or 2 billion, including 9% with severe food insecurity (FAO et al., 2020)	Severe: up 0.9% Moderate: up 2.3%
	Wasting (being underweight for height)[4, 6]	WHO target: Reduce and maintain childhood wasting at less than 5% by 2025 and less than 3% by 2030 (WHO & UNICEF, 2017)	2012	8%	2019	6.9% (moderate and severe) or 47 million children (UNICEF et al., 2020)	Down 1.1%
	Stunting (being short for age)[4, 5, 6]	WHO target: 40% reduction in the number of children under five years of age who are stunted by 2025 and 50% by 2030 form 2016 (WHO & UNICEF, 2017)	2012	24.6% (UNICEF et al., 2020)	2019	21.3% (moderate and severe) or 149 million children under five years of age (UNICEF et al., 2020)	Down 3.3%
	Overweight children (children <5 years with a Body Mass Index (BMI) over 30 – calculated as weight/height2)[4, 5, 6]	WHO 2025 target: No increase in child overweight (WHO & UNICEF, 2017)	2012	4.9%	2019	5.3% or 38.3 million under five years of age are overweight (FAO et al., 2020)	Up 0.7%

	Element	International target/s	Baseline year	Baseline estimate	Latest assessment year	Latest global estimates (with population estimates where available)	Change to date (global)
Nutrition	Obesity (Adults with a BMI over 30)	WHO 2025 target: Halt the rise in levels (WHO & UNICEF, 2017)	2012	11.8%	2016	13.1% or 677.6 million obese adults (GNR, 2020)	Up 1.3%
	Low birthweight (less than 2500 g)[6]	WHO 2025/2030 target: 30 % reduction in low birth weight (WHO & UNICEF, 2017)	2012	15%	2015	14.6% (FAO et al., 2020)	Down 0.4%
	Anaemia (iron deficiency)	WHO 2025/2030 target: 50 % reduction of anaemia (iron deficiency) in women of reproductive age (WHO & UNICEF, 2017)	2012	30.3%	2016	2016 32.8% (FAO et al., 2020)	Up 1.5%
Food safety	Foodborne Disease Burden	None established	2010	Unsafe food caused 600 million cases of foodborne diseases and 420 000 deaths equivalent to 33 million years of healthy lives are lost WHO Foodborne Disease Burden Epidemiology Reference Group (FERG 2007-2015)	Not applicable (N/A)	N/A – only baseline available	Unknown – only data for 2010 published
Poverty and inequality	Poverty	SDG1: By 2030 eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.90 a day (World Bank, 2018)	2015	10% or 734 million (World Bank, 2018)	2019	8.2% (UN, 2021)	Down 1.8%

Poverty and inequality	Affordability	None	2019	% population that cannot afford an energy-sufficient diet = 4.6% FAO et al., 2020)	–	N/A – only baseline available	Unknown – this is a new indicator without historical data
				% population that cannot afford a nutrient-adequate diet = 23.3% (FAO et al., 2020)			
				% population that cannot afford a healthy diet = 38.3% or 3 billion (FAO et al., 2020)			

Notes to Table 1:

1. Regional estimates were included when more than 50% of the population was covered. To reduce the margin of error, estimates are presented as three-year averages (FAO et al., 2020).2 FAO estimates of the number of people living in households where at least one adult has been found to be food insecure (FAO et al., 2020).
2. Country-level results are presented only for those countries for which estimates are based on official national data or as provisional estimates, based on FAO data collected through the GallupR World Poll, for countries whose national relevant authorities expressed no objection to their publication (FAO et al., 2020).
3. For regional estimates, values correspond to the model predicted estimate for 2019. For countries, the latest data available from 2014 to 2019 are used (FAO et al., 2020).
4. For regional estimates, values correspond to the model predicted estimate for 2012. For countries, the latest data available from 2005 to 2012 are used (FAO et al., 2020).
5. Wasting, stunting and overweight under 5 years of age and low birthweight regional aggregates exclude Japan (FAO et al., 2020).

4. INTERCONNECTED FOOD SYSTEMS DRIVERS THAT AFFECT THE ACCESS TO SAFE AND NUTRITIOUS FOOD FOR ALL

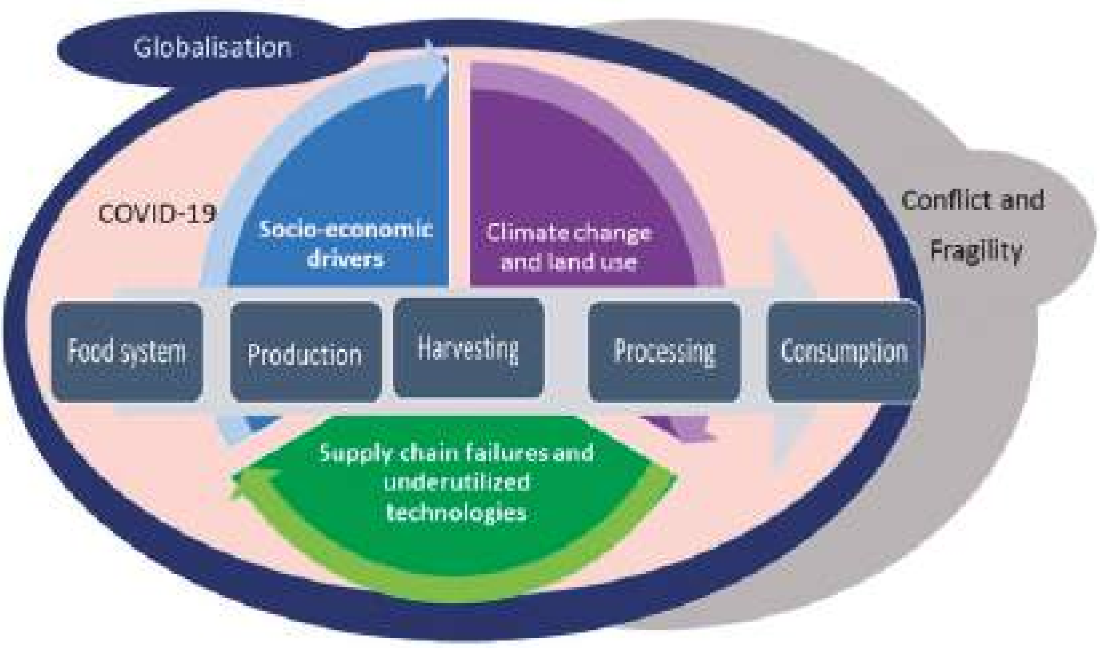
Several interconnected socio-economic and biophysical food systems drivers affect access to safe and nutritious food. Nutrition is both a health and food system concern. While some drivers of food systems are global (e.g. trade liberalisation, climate change), others are regional, national and sub-national (e.g. conflicts). At the same time, many are differentiated across geographies (e.g. poverty, demography, technologies, land degradation). Below, we provide a brief overview of the main drivers, depicted in Figure 2. At the centre of the diagram is the food system, driven by socio-economic, supply chain and climate change and land-use drivers (depicted by the segmented circle). The drivers and the food system are influenced by globalisation and the global COVID-19 pandemic. In certain contexts, the drivers and the food system are also affected by conflict and fragility.

a) Socio-economic drivers

There is a vast array of socio-economic drivers that increase the global food demand, including population growth (Gerten et al., 2020), the westernisation of diets, increased food waste and overweight (including obesity) (Hasegawa et al., 2019), increased demand for animal-sourced foods in diets leading to increased demand of feed from arable crops (Mottet et al., 2017), and rapid urbanisation (van Vliet et al., 2017). These trends could cause a doubling of food demand by 2050 and will require a mean global increase of crop yields by over 30% from 2015 for a range of scenarios without climate change (FAO, 2018), a value lower than in previous projections that were assuming rapid economic growth (Alexandratos and Bruinjsma, 2012).

Globalisation. Lockdowns caused by the COVID-19 pandemic of zoonotic origin have disrupted the production, transportation, and sale of nutritious, fresh and affordable foods, forcing millions of families to rely on nutrient-poor alternatives (Foreet al., 2020). International food trade can increase the diversity of diets and has established a global standard food supply, which is relatively species-rich regarding measured crops at the national level, but species-poor globally (Khoury et al., 2019). Globalised food trade can also contribute to unsustainable water use (Rosa et al., 2019) and land degradation (IPCC, 2019). The availability of cheap, high-energy, fatty and sugary foods, the high price of nutritious fresh foods and the demand for more 'westernised' and often obesogenic foods increases the incidence of nutrition-related NCDs (Chaudhary et al., 2018). Nevertheless, globalised supply chains support the wide distribution of food, reducing shortages in import-dependent regions (Janssens et al., 2020), im-

Figure 2 Food system context and drivers related to Action Track 1.



proving seasonal availability and often reducing food loss through technological advances in processing, packaging and storage (Zilberman et al., 2019).

Demography and urbanisation. Although population growth has slowed globally, the population in the 47 least developed countries (mostly in Africa and Asia) is projected to double between 2019 and 2050. By 2030, the number of youth in Africa will have increased by 42%. Nevertheless, in 2018, for the first time in history, the proportion of older persons (above 65) outnumbered children under five years, a trend that is predicted to continue (UNDESA, 2019). A growing proportion of older people will put a strain on the health system and change nutritional needs and dietary preferences. Ageing is accompanied by multiple physiological changes that affect diets and nutrition. This may include a lower sense of taste and/or smell; reduced appetite; poor oral health and dental problems; lower gastric acid secretion that may affect the absorption of minerals and vitamins; loss of vision and hearing and reduced mobility that may limit mobility and affect elderly people's ability to shop for food and prepare meals (WHO, 2015b). Moreover, by 2050, 68% of the global population could be urban, shifting the proportion of producers to consumers, changing consumption patterns (demand), driving land take and putting extra pressure on soil resources (Barthel et al., 2019, van Vliet et al, 2019).

Poverty and inequality. Poverty traps millions in poor nutrition, depriving them of their potential (Victoria, 2008). The prevalence of undernutrition and overweight adults are directly linked with relative food prices (Headey and Alderman, 2019). Healthy diets cost between 60 and 400% more than nutrient-adequate and energy-sufficient diets, respectively (FAO et al., 2020). More than 1.5 billion people cannot afford a nutrient-adequate diet and over three billion cannot afford even the cheapest healthy diet (FAO, 2020). Food system disruptions caused by COVID-19 measures aggravate this situation (Headly et al., 2020). The out-of-pocket costs on health care spent by the poorest billion due to NCDs and injuries may be high, accounting for 60-70% of the public health care costs in low-income and lower-middle-income countries (Zuccala and Horton, 2020). In total, it has been estimated by the World Bank that under and malnourishment costs 3% of global GDP and overweight and obesity another 2% of GDP (Jaffee et al., 2018).

Women play a key role in multiple components of food systems and in decisions over food choices. Nonetheless, inequalities and barriers related to access to farming opportunities and services such as extension, credit, digital platforms for knowledge and market access constrain their participation relative to men (Quisumbing, 2011). Inequalities and barriers also affect the nutrition and health of minorities and off-farm and food system workers (including migrants and undocumented workers), which is a barrier to food system and societal transformation (CFS, 2020).

Conflict and fragility. Conflict can be an outcome and cause of food insecurity. Increased competition for natural resources leads to conflict and political fragility, exacerbated by the failure of traditional conflict resolution mechanisms to adapt to the new governance system of communities (SOFI, 2017). Government and political institutions (municipalities, legal systems and political party structures) have not adapted to the social fabric they presently govern, constraining development and also affecting development and the delivery of humanitarian aid.

While widespread famine has largely been eradicated, the nature of food crises has changed in recent times. FSIN (2020) reports that in 2019, about 135 million people were affected by crisis levels of acute food insecurity, reflecting an increase of 11 million people from the previous year (FSIN Food Security Information Network, 2020). While these crises are largely driven by conflict and economic downturns, they have a severe effect on the ability of people to access food. The provision of food transfers in emergency situations may alter the food preferences of communities, leading to changes in production and consumption past-conflict.

The largest numbers of acutely food-insecure people are in Africa, where extreme weather events in the Horn of Africa and Southern Africa have led to widespread hunger. In many parts of the world, armed conflicts, intercommunal violence and other localised tensions create insecurity (FSIN, 2020). Adverse climate events and stresses compound violence, displacement and disrupted agriculture and trade. Often those affected by crises flee to neighbouring countries, putting additional stress on the international humanitarian response system and on the food systems of the host countries. Women and girls are disproportionately affected by crises. Populations in crisis are disproportionally vulnerable to the impact of the COVID-19 pandemic and have little capacity to cope with the health and socio-economic aspects of the shock (FSIN, 2020). WFP predicts that the number of people in LMICs facing acute food insecurity will nearly double to 265 million by the end of 2020 (WFP, 2020). Moreover, fragile and extremely fragile countries are disproportionally burdened by high levels of malnutrition compared to non-fragile countries (GNR, 2020).

b) Supply chain failures and under-utilised technologies affecting the supply of food

The focus of food supply has shifted over the past few decades from 'feeding the world' to 'nourishing the world', but technological advancements still lag behind and many supply-side factors and failures affect the ability of the food system to sustainably (see Box 1) ensure access to safe and nutritious for all. In many developing countries (especially in Africa), supply chain failures and the under-utilisation of technology are major constraints to the transformation of food systems to achieve this access. More than half of the calories consumed by humans are provided by three major cereal crops (rice, maize, and wheat) with a high-calorie output and current research investments are positively correlated with the energy output of crops, with a number of crop species (e.g. sweet potato, potato, wheat, broad bean, and lentil) under-researched relative to their contribution to healthy human nutrition (Manners and Van Etten, 2018). Orphan crops that are usually well adapted to low-input agricultural conditions have received little attention from researchers (Tadele, 2019). There is a growing recognition that the development of perennial versions of important grain crops and grasses could expand options to ensure food and ecosystem security (Glover et al., 2010). Viable high biomass perennial grain crops could be further developed in agroecosystems that regenerate soils and capture other important ecosystem functions (Crews and Cattani, 2018). In the same way, this lack of research applies to some fruit and vegetable crops and local livestock local breeds, especially for small ruminants as well as fish.

Closing yield gaps on underperforming lands and increasing cropping efficiency would have considerable potential to meet an increasing food demand (Foley et al., 2011). One main reason why yield gaps exist is that farmers do not have sufficient economic incentives to adopt yield-enhancing seeds or cropping techniques, including mechanisation, precision and digital agriculture. Moreover, a lack of access to extension services, to formal credit and cooperative membership often limits technology adoption, which is associated to positive household welfare effects (Wossen et al., 2017). While efficiency and substitution are steps towards sustainable intensification, system redesign may be essential for agro-ecological intensification through e.g. integrated pest management, conservation agriculture, integrated crop and biodiversity, pasture and forage, trees, irrigation management and small or patch systems (Pretty et al., 2018).

Currently, 25-30% of total food produced is lost or wasted (IPCC, 2019), equating to about one-quarter of land, water, and fertiliser used for crop production (Shafiee-Jood and Cai, 2016). Food losses and food waste occur throughout the food chain. They constrain food system sustainability due to their adverse effects on food security, natural resources, environment, climate and human health (e.g. toxic emissions from incineration) (Xue et al., 2017).

Plant biotechnologies are mostly used for fibre and animal feed, less often for food because of regulatory constraints and intellectual property rights barriers (Barrows et al., 2014). New and innovative technologies such as biotechnologies, precision agriculture and digital agriculture, alternative protein sources, under-utilised food sources and the use of biomass for bioenergy and green chemicals need to be harnessed to improve food systems (reviewed below). However, such advances can also drive negative food system changes. For example, biofuel production based on grains from food crops, can drive up staple food prices and compete for land, exacerbating inequalities.

c) Climate change, land-use change and natural resource degradation

Climate change, including increases in frequency and intensity of extremes, has adversely impacted food security, affecting the yields of some crops (e.g. maize and wheat) and on pastoral systems in low latitude regions (IPCC, 2019). Climate change may aggravate food system problems in countries with delicate food security balances and relatively high levels of vulnerability to climate change due to the large-scale use of scarce resources (water, land, etc.) for feed and food production for exports, particularly in the case of mono cropping. Diets and cropping patterns may change as climate factors constrain the production of traditionally grown crops.

With increasing warming, the frequency, intensity and duration of heatwaves, droughts and extreme rainfall events are projected to increase in most world regions, increasingly threatening the stability of food supply (IPCC, 2019). For example, Gaupp et al. (2020) found an estimated 86% probability of losses across the world's maize breadbaskets with warming of 4 °C, compared to 7% probability for 2°C warming under business-as-usual conditions and without considering crop adaptation to climate change. Likewise, in a business-as-usual scenario, Alae-Carew et al's. (2020) review of predicted changes in environmental exposures has reported likely reductions in yields of non-staple vegetables and legumes. Where adaptation possibilities are limited, this may substantially change their global availability, affordability and consumption in the mid to long term (Alae-Carew et al., 2020; Scheelbeek et al., 2018). The nutritional quality of crops may also be affected by rising atmospheric CO2 levels through reduced proteins and micro-nutrients contents (IPCC, 2019). Labour productivity is also likely to reduce with increasing temperatures (Watts et al., 2021).

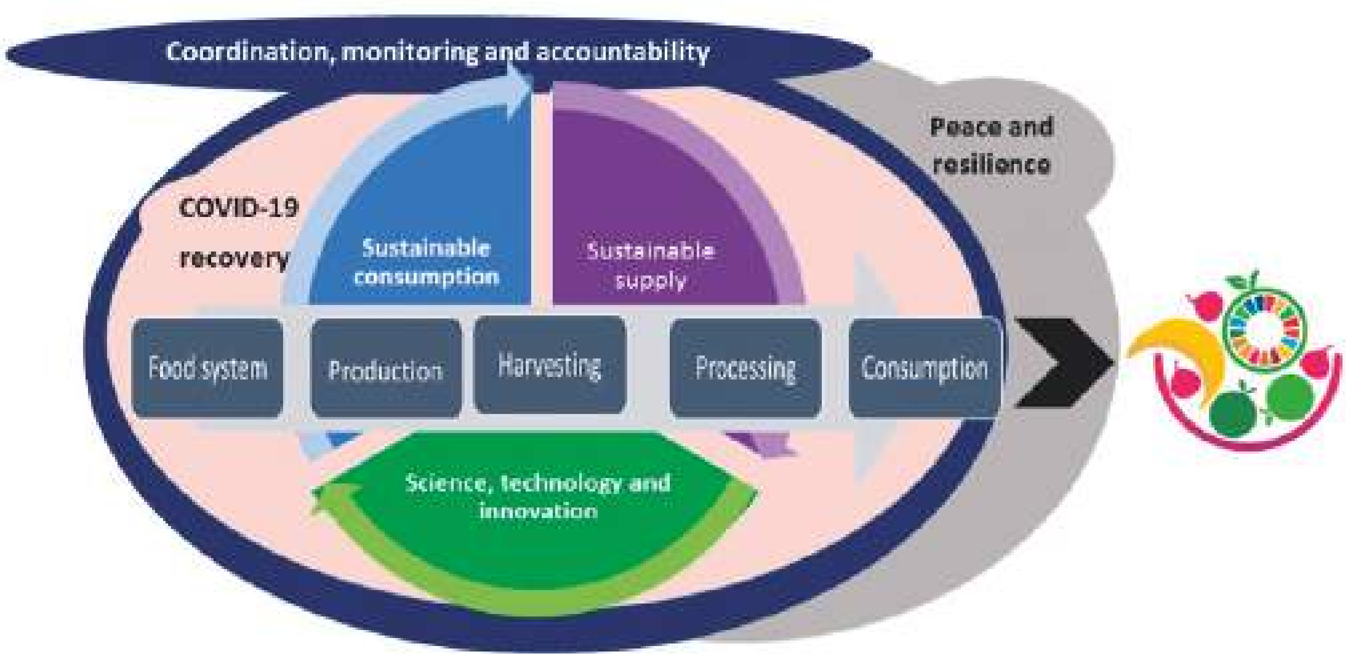
The global food system (from farm inputs to consumers) emits about 30% of global anthropogenic greenhouse gases (GHG), contributes to 80% of tropical deforestation and is a main driver of land degradation and desertification, water scarcity and biodiversity decline (IPCC, 2019). About one-quarter of the Earth's ice-free land area is subject to human-induced degradation and about 500 million people live within areas undergoing desertification (IPCC, 2019). By 2050 land degradation and climate change could lead to a reduction of global crop yields by about 10% with strong negative impacts in India, China and sub-Saharan Africa resulting in the displacement of up to 700 million people (Cherlet et al., 2018). Around 2 billion people live within watersheds exposed to water scarcity and this number could double by 2050 (Gosling and Arnell, 2016). Future agricultural productivity in the tropics is also at risk from a deforestation-induced increase in mean temperature and the associated heat extremes and from a decline in rainfall (Lawrence and Vandecar, 2015). Over half of the tropical forests worldwide have been destroyed since the 1960s, affecting the lives of 1 billion poor people whose livelihoods depend on forests and equalling a mass extinction event if tropical deforestation continues unabated (Alroy, 2017).

5. TRANSFORMING FOOD SYSTEMS IS KEY TO SAFE AND NUTRITIOUS FOOD FOR ALL

Business-as-usual is not an option with the future of food and nutrition security in jeopardy (FOFA, 2018). Changing the path of our future will demand a structural transformation (transitioning from low productivity and labour-intensive economic activities to higher productivity, sustainable and skill-intensive activities) of food systems. This will require changes in the allocation of resources and research attention to factors beyond production will be necessary to transition to more sustainable patterns of production and consumption (CFS, 2020). More concerted effort is needed to coordinate activities, monitor progress more closely and greater accountability from all players across the food system. Priority should be given to the establishment of functional problem-solving institutions which address the core challenges facing each of the various components of the global food systems.

A global social compact (an implicit agreement among the members of a society to cooperate for social benefits) is needed to manage the demand and consumption drivers and harness science, technology and innovation to improve the sustainable production of enough food to ensure access to affordable, safe and nutritious foods for all (Figure 3). The sections below identify some of the levers for change.

Figure 3 Food system context and drivers related to Action Track 1.



a) Coordination, monitoring and accountability

The ambition of the CFS is to be "the most inclusive international and intergovernmental platform for all stakeholders to work together in a coordinated way to ensure food security and nutrition for all" (CFS, 2021). Moreover, UN agencies and their partners have converged through various mechanisms for food security coordination (e.g. FSIN, the Global Network Against Food Crises, expanding the SOFI collaborators, the CFS Global Strategic Framework, etc.). Strengthening the global governance and accountability regarding safe and nutritious food for all and sustainable food systems is key for meeting the challenges ahead and will require cross-sectoral integration of policies. Nonetheless, agriculture, development and trade policies that affect access to food as well as other dimensions of food systems are often dealt with in separate fora (De Schutter, 2013). Therefore, improved coordination, monitoring and accountability across the food system and among all stakeholders is necessary, including sharing knowledge, building capacity, better measurement, updated data, better modelling for foresight, scenarios and case studies and access to documented success stories. Food systems bring together elements from various sectors of society: agriculture, consumer affairs, food processing, health, trade, water and sanitation, women's and child welfare, etc., challenging the sectoral organisation found in most countries.

If we are to transform food systems to ensure safe and nutritious food for all from sustainable food systems, a concerted effort is needed to develop a global compact – a non-binding agreement to encourage the transformation of food systems – and appropriate accountability of all stakeholders to monitor agreed-on transformation targets. Integrated, science-based policies (health and nutrition, food and agriculture, climate and environment) would allow reinforcing accountability at both national and international scales.

Advances in information technology and data science play an important role in enabling rapid assessment of situations, monitoring and decision-making and adaptive learning. An integrated global food system model is needed as existing models (see Valin et al., 2014; Khanna and Zilberman, 2012) do not have consistent global coverage and are not designed to assess the impacts of all of the elements of food systems. Strengthening national policy scenarios and foresight is also necessary (Schmidt-Traub et al. 2019). Moreover, improved indicators of food systems (see SOFI, 2020) are required (see Sukhdev et al. 2018, Chaudhary et al. 2018 for examples), that could provide more holistic measures that capture the four elements addressed by Action Track 1, namely safety, nutrition, inequality and sustainability.

Rigorous global monitoring systems require global collaboration, updated information, and investment with significant returns. The monitoring of underlying systemic risks (perhaps using artificial intelligence or machine learning) as well as food system indicators is essential to identify threats/pressure at an earlier stage. A task force charged with global monitoring and data collection opportunities about agri-food systems, could provide a clearinghouse for the multiple (often duplicated) data held by UN agencies and public and private organisations. While some effort has been made to coordinate international actions to address crises, access to food requires targeted interventions for the most vulnerable. Two-way real-time and artificial intelligence applications to collect information of systemic risks and food systems and disseminate information to various stakeholders and beneficiaries are needed in last-mile and crises situations and in regions disproportionately affected by the COVID-19 pandemic food system disruptions. This could include driving supply-side demand through food banks, social grants, subsidised meals, vouchers and other food assistance (including through e-commerce systems) (WFP, 2017).

b) Influencing food demand and dietary changes

There are several ways to reduce demand on the global food system in both the short and long term and make nutritious foods more available and affordable (see Herrero et al., 2021). Some of these ways may be by accelerating demographic transitions, increasing incomes, reducing food losses and waste and changing diets.

Household food waste is proliferating in emerging economies and is likely to increase without deliberate effort to curb waste (Barrera and Hertel, 2020). Halving food losses and waste is a target of SDG 12 that could help feed more people, benefit climate and the environment and conserve water (Kummu et al., 2012; Searchinger et al., 2018; IPCC, 2019). This requires changes along supply chains (agricultural production, food processing, distribution/retail, restaurant food service, institutional food service, and households) through improved logistics and processing technologies, economic incentives, regulatory approaches and education campaigns (Read et al., 2020; Barrera and Hertel, 2020). The amount of food waste/loss varies greatly from region to region, and therefore context-specific interventions are crucial (Hodson et al., 2021).

Private investment is needed to develop food processing, refrigeration, storage, warehousing as well as retail markets to reduce food waste. Vertical integration of food chains can shorten chains to the benefit of smallholder farmers while trade can expand market opportunities. Compared to a business-as-usual scenario, a combined scenario targeting undernourishment while also reducing over-consumption and food waste would reduce food demand by 9% in 2050 (Hasegawa et al., 2019).

Because of the strong associations between female education, fertility and infant mortality, alternative education scenarios alone (assuming similar education-specific fertility and mortality levels) lead to a difference of more than one billion people in the world population sizes projected for 2050 (Lutz and Samir, 2011; Samir and Lutz, 2017) and could therefore reduce the rise in food demand.

Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, complemented by animal-sourced food produced in resilient, sustainable and low-GHG emission systems present major opportunities for adaptation and mitigation of climate change while generating significant co-benefits in terms of human health (Springmann et al., 2018; IPCC, 2019, Jarmul et al., 2020). 'Healthy sustainable diets' can be defined by optimisation procedures (Donati, et al., 2016). However, most diets have trade-offs between nutritional values, affordability and environmental issues (Headey and Alderman, 2019).

Populations with a high prevalence of undernutrition and micronutrient deficiencies (Fanzo, 2019) benefit from increasing the consumption of animal-sourced products due to the bioavailability of key micro-nutrients (Perignonet al., 2017). Many highly nutritious foods may simply be unaffordable to poorer populations and displaced by cheap, nutrient-poor foods. Moreover, a balance is necessary between meeting the demand for diversified, nutritious and affordable food and minimising the time and energy to prepare meals.

Policies can create incentives for change. Urgent public policy action is needed to create incentives for creating healthy, sustainable food systems and delivering safe, nutritious and affordable foods for all. Policy options could be used to manage food demand, shift consumption patterns, reduce the environmental footprint of food systems and ensure equity across the food system. A wide range of well-established and relatively inexpensive policy options and interventions are available for improving nutrition at the individual level (Buckhman et al., 2020; Hawkes et al., 2020; Bhutta et al., 2008). Policies that enable healthy food environments (such as sugar taxes, educational food labelling, reducing salt, the prohibition of trans-fats and a reduction in the use of high-fructose corn syrup) are core to improving food environments and limiting the burden of NCDs. Increasing the diversity of food sources in public procurement, health insurance, financial incentives and awareness-raising campaigns can potentially influence food demand, reduce health-care costs, contribute to reduce GHG emissions and enhance adaptive capacity.

Increased income can drive food demand, especially in terms of diversification away from staple crops to more diverse and nutrient-dense foods (diary, fruit, meat, nuts and vegetables). Likewise, income from social protection programmes can drive changes in dietary composition and quality (Alderman, 2016). The evidence reviewed in this paper indicates that subsidies on fortified foods can have positive nutritional effects, and in-kind transfers may limit food deficits during periods of currency or price volatility. The affordability of healthy diet can be improved with distribution of bio-fortified food in government schemes, cash transfers and nutrition programmes. However, price subsidies and in-kind assistance have complex interactions on markets and purchasing decisions with both negative implications and benefits (Alderman, 2016).

c) Shifting to more sustainable consumption and production within planetary boundaries

Nutrition outcomes in developing countries are affected by agriculture in several ways: as a source of food for household consumption and of income, through the role of food prices and agricultural policies, through the role of women's employment in agriculture for nutrition, child care and child feeding and their own nutritional and health status (Gillespie and van den Bold, 2017).

There are more than 570 million farms worldwide, most of which are small and family-operated. Between 1960 and the turn of the century, the average farm size decreased in most lower- to middle-income countries, whereas it increased in most high-income countries (Lowder et al., 2016). The diversity of agricultural production diminishes as farm size increases (Herrero et al., 2017). Hence, as farm size increases, the production of diverse nutrients and viable, multifunctional, sustainable landscapes requires efforts to maintain production diversity (Herrero et al., 2019), which may lead to increased dietary diversity (Pellegrini and Tasciotti, 2014). Targeted policies that focus on the farmer may incentivise positive changes in landscapes, production diversity and dietary diversity.

In turn, diversification in the food system (e.g. implementation of agro-ecological production systems, broad-based genetic resources, combined with balanced diets) can enhance adaptation to increased climate variability under climate change (IPCC, 2019). Diversified agro-ecological systems can play a role in meeting health and nutrition goals while also reducing environment-related health risks caused by conventional agriculture through water and air pollution, and more specifically by pesticides, antibiotics and inorganic fertilisers (Frison and Clément, 2020). Compared to conventional agriculture, organic agriculture generally has a positive effect on a range of environmental factors, including above and belowground biodiversity, soil carbon stocks and soil quality and conservation, but it has weaknesses in terms of lower productivity and reduced yield stability (Knapp and van der Heijden, 2019).

Sustainable land management can bridge yield gaps and avoid deforestation while providing climate change adaptation and mitigation and land degradation co-benefits in croplands and pastures (Smith et al., 2020). This can be achieved by increasing soil organic carbon (Soussana et al., 2019), agroforestry, erosion and fire control, improved irrigation water and fertiliser management, heat- and drought-tolerant plants (Smith et al., 2020). For livestock, sustainable options include better grazing land management, improved manure management, higher-quality feed, and use of breeds and genetic improvement (Herrero et al., 2016). Under stringent global climate change mitigation policy, risks for food security would be increased (Hasegawa et al., 2018) through competition for land between food production, bioenergy and afforestation be it driven by local or foreign investment in land (Cotula, 2014). Nevertheless, increasing and valuing soil carbon sequestration on agricultural land would allow the reduction of these negative impacts by approximately two-thirds (Frank et al., 2017). The large-scale deployment of bioenergy options such as afforestation, energy crops, carbon capture and storage has adverse effects on food security, but small scale projects with best practices may deliver co-benefits (Smith et al., 2020).

Increased demand for fish and seafood has threatened fisheries and the sustainability of ocean resources. Limited attention has been given to fish as a key element in food security and nutrition (HLPE, 2014). The aquaculture industry has emerged and increasingly fills the seafood supply gap to meet growing demand. Overfishing and relatively high waste (often due to catching under-sized fish) pose environmental and biodiversity challenges, threatening the long-term sustainability of fishery resources (HLPE, 2014). Additional challenges in production facilities such as marine feed supply, antibiotic use and in waste recycling need to be overcome to further develop aquaculture (Belton et. al., 2020). The impacts of activities such as oil drilling, energy installations, coastal development and construction of ports and other coastal infrastructures, dams and water flow management (especially for inland fisheries) affect aquatic productivity. The impact of these activities on the habitats that sustain resources (e.g. erosion and pollution) and the livelihoods of fishing communities – such as the denial of access to fishing grounds or displacement from coastal settlements – need to be carefully balanced with the growing demand for resources (HLPE, 2014).

Ensuring that food prices reflect real costs, including major externalities caused by climate change, land and water resources degradation and biodiversity loss is necessary to address artificial price distortions, reduce food waste, internalise the costs of externalities (including the public health impacts) and, at the same time, ensure decent incomes and wages for farmers and food system workers. However, a true costing of food would on average increase food prices. Food assistance policies that do not distort market and labour incentives can meet emergency food needs and improve access to food. Trade can help to improve food availability, diversify diets and smooth price volatility (MacDonald et al., 2015).

d) Harnessing science and innovation and managing risks

Structural transformation to a more sustainable food system can bring about efficient and more rapid productivity growth through investment in research and development over the long term (Fuglie et al., 2020). Science should increasingly inform solutions and generate knowledge that is actionable to transform food systems and reach safe and nutritious for all (Arnott et al., 2020). Since policy agendas are largely set at national and local scales, the translation of global-scale scientific assessments into actionable knowledge at national and local scales is needed.

New and emerging technologies appropriate for one health, climate change adaptation and mitigation, as well as disaster preparedness, could be game-changers for overcoming challenges and building system resilience. Nonetheless, their development should be guided by assessing their socio-economic, ethical and environmental impacts. Evidence-based assessment is needed of the risks and benefits associated with new technologies. Research is also needed to understand the diffusion modes of traditional knowledge and social innovations to support the conservation of common goods in more participatory, collaborative, inclusive and equitable ways.

Advances in science and technology such as genome editing (Khatodia et al., 2016), precision agriculture and digital agriculture (Basso and Antle, 2020), agroecology (Caquet et al., 2021), vertical farming, alternative protein sources (e.g. algae, insects), active packaging and blockchain technologies (Kamilaris et al., 2019), artificial intelligence and big data analysis (Wolfert et al., 2017) and whole-genome sequencing in food safety (Deng, Bakker, & Hendriksen, 2016) have the potential to meet a number of food system challenges. However, adapting these technologies to local conditions, making them accessible to farmers and retain much of the gain among consumers and the rural communities, is challenging, especially for developing economies, smallholder farmers and small businesses. Therefore, investments in science-based, participatory processes to map out realistic and equitable options are needed (Basso and Antle, 2020).

The importance of agriculture in producing non-food products (biofuels, chemicals, biomaterials) and in supporting ecosystem services is increasingly recognised in the context of the bioeconomy, which targets an increased reliance on renewable sources to address climate change (Zilberman, 2014). A circular bioeconomy envisions developments in industrial biotechnologies to generate co-products, by-products and waste recycling, thereby generating an overall increased input efficiency of agricultural systems producing bio-based products in diversified agro-ecological landscapes (Therond et al., 2017; Maina et al., 2017).

Global and regional data sharing systems (including machine learning) based on the FAIR principles (findable, accessible, interoperable and reusable data) (Mons et al., 2017) can advance food systems knowledge and enhance the accountability of all stakeholders of the food systems. The use of open-source platforms for data and code sharing should be encouraged to stimulate global learning.

Table 1 shows the fragmented nature of data related to this Action Track, with global reports focussing on single elements. National nutrition assessments are costly and infrequently conducted, constraining the monitoring of progress and the impact of interventions at scale. Even where the indicators have been included in the SDG indicator set, current data on foodborne diseases, some malnutrition indicators (such as wasting), poverty and inequality data are not updated or are missing comparative baselines. Very few sex-disaggregated indicators are available, constraining analysis and the tracking of progress towards gender equality. The upcoming *Countdown on Food System Transformation* mechanism may support the effort to bring together various indicators in a systematic framework for monitoring and evaluation.

Increasingly, risk assessment tools will be needed to drive food safety policy and standards and optimise surveillance, detection and early warning systems of zoonotic diseases for both the formal and informal sectors (Di Marco et al., 2020) and crop diseases (Mohanty et al., 2016). Modernising our food safety and biosecurity risk management systems is an integral part of the food system transformation required to meet food and nutrition security needs. This will require a science- and risk-based approach for production of safe food within a food systems approach.

6. CONCLUDING MESSAGES

Action to address safety, malnutrition, poverty and inequality, as well as climate and environmental issues, through food systems transformation will undoubtedly bring large health, social, economic, ecological and development co-benefits and savings on public expenditure while supporting several interrelated SDGs. A range of priority actions to speed up progress towards international targets and scale up the solutions proposed in section 5 can be taken in the short-term, based on existing knowledge, while supporting longer, more sustainable responses with significant co-benefits. Future actions will have to be iterative, coherent, adaptive and flexible to maximise co-benefits and minimise trade-offs. Many recommended policy changes and interventions have win-win potential for food security, health and the environment. However, other choices will have adverse or unintended impacts on the interconnected drivers affecting food systems and their outcomes.

Adopting a whole-system approach in policy, research and monitoring and evaluation is crucial to manage trade-off and externalities from farm-level to national scales and across multiple sectors and agencies. Ultimately, context matters and comprehensive national action plans are crucial for setting out actions suited to the particular economic, agricultural, social and dietary preferences of the particular nation. Careful consideration of the trade-offs and co-benefits of any actions will be necessary at different levels (sub-national, national, regional and global). Likewise, there may be ‘winners’ and ‘losers’ in each action adopted to transform to more sustainable food systems. The losses and gains will vary depending on the context but could include a loss of income and livelihoods across the food system, such as would happen with a reduction in the production and consumption of animal-sourced foods or the implementation of seasonal banning of fishing to allow for the regeneration of marine resources. Such shifts could lead to the marginalisation and stigmatisation of people in the food system who have not yet been considered as vulnerable or marginalised.

Including all stakeholders in discussions, policy-making and evaluation processes is essential for the inclusive transformation of food systems at all levels. Strengthening collaboration between research, the private sector and policy-makers is pivotal in creating food environments and guiding consumers' choice in practical and implementable ways. The elaboration and implantation of National Food Systems Plans will be essential instruments for bringing the relevant public sectors and diverse stakeholders together.

Adaptive learning and new knowledge must be shared globally to accelerate our capacities to meet existing and future challenges. Substantial public, private and international investment is necessary to faster progress towards the targets and recover from the setbacks of the COVID-19 pandemic. Improved international cooperation and coordination of the food system is necessary, including the establishment of a comprehensive monitoring, evaluation and early warning system with comprehensive indicators, transparency and commitments of all stakeholders. For example, bringing all of the indicators in Table 1 into one annual food system monitoring report would facilitate cooperation among UN agencies. Creating a food system compass could be based on bottom-up pathways developed at national scale to reach food systems targets supporting an ensemble of global-scale and integrative food systems models. Establishing such a system will require capacity development for comprehensive foresight, scenario and predictive modelling to better understand uncertainties, trade-offs and impacts of various change pathways. More research is needed to identify the most adequate, affordable, healthy and sustainable diets across different contexts. More frequently collected nutrition and poverty data are necessary to provide more data points for monitoring change and progress. Innovative indicators such as the affordability of adequate, nutritious and healthy diets are vital to bring the three elements of safety, nutrition and inequality together.

The costs of acting and not acting on the key drivers of diet and food system change and the impact of these changes and shifts are required for effective decision-making. For example, the cost of nutrition interventions is relatively low per unit compared to the long-term losses in human potential and incomes for poorer people. The cost of NCDs to the health system is significantly higher per unit that the cost of scalable interventions. Rapid reductions in anthropogenic GHG emissions across all sectors can reduce the negative impacts of climate change on food systems in the long term (similar for land and for water restoration).

Research and technology advances are essential to solve critical constraints and offer many opportunities to improve productivity, food safety and reduce food losses and waste, as well as GHG emissions. Capacity-building, property rights, technology development, transfer and deployment and enabling financial mechanisms across the food system can support livelihoods and increase incomes. Greater cooperation regarding trade could overcome constraints and barriers.

Safe and nutritious food for all requires a transformation of food systems, changing both supply and demand of food in differentiated ways across world regions: bridging yield gaps and improving livestock feed conversion, largely through agro-ecological practices and agroforestry, deploying at scale soil carbon sequestration and agricultural greenhouse gas abatement, reducing food losses and wastes, as well as over-nourishment and changing the diets of wealthy populations. Global food systems sustainability also requires halting the expansion of agriculture into fragile ecosystems while restoring degraded forests, fisheries, rangelands, peatlands and wetlands.

REFERENCES

1. Alae-Carew, C., Nicoleau, S., Bird, F.A., Hawkins, P., Tuomisto, H.L., Haines, A., Dangour, A., Scheelbeek, F.P. (2020). The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: A systematic review. Environ. Res. Lett. 15 023002.
2. Alexandratos, N., & Bruinsma, J. (2012). World Agriculture Towards 2030/2050: the 2012 revision. Rome: Agricultural Development Economics Division, Food and Agriculture Organization of the United Nations.
3. Alroy, J. (2017). Effects of habitat disturbance on tropical forest biodiversity. Proceedings of the National Academy of Sciences, 114(23), 6056-6061.
4. Alderman, H. (2016). Leveraging Social Protection Programs for Improved Nutrition: Summary of evidence prepared for the global forum on nutrition-sensitive social protection programs, 2015. World Bank, Washington DC.
5. Arnott, J.C., Mach, K.J., Wong-Parodi, G. (2020). Editorial overview: The science of actionable knowledge. Current Opinion in Environmental Sustainability, 42:A1-A5.
6. Barrera, E. L., Hertel, T. (2020). Global food waste across the income spectrum: Implications for food prices, production and resource use. Food Policy, 101874.
7. Barthel, S., Isendahl, C., Vis, B. N., Drescher, A., Evans, D. L., & van Timmeren, A. (2019). Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. The Anthropocene Review, 6(1-2), 71-97.
8. Basso, B., Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. Nature Sustainability, 3(4), 254-256.
9. Belton, B., Reardon, T. & Zilberman, D. Sustainable commoditization of seafood. Nat Sustain 3, 677-684 (2020). https://doi.org/10.1038/s41893-020-0540-7.
10. Bhutta, A; Ahmed, T; Black RE; Cousens, S; Dewey, K; Giugliani, E; et al. (2008). What works? Interventions for maternal and child undernutrition and survival. The Lancet| volume 371, issue 9610, p417-440 DOI:https://doi.org/10.1016/S0140-6736(07)61693-6.
11. Bukhman, G; Mocumbi, AO; Atun, R; et al. for the Lancet NCDI Poverty Commission Study Group. (2020). The Lancet NCDI Poverty Commission: bridging a gap in universal health coverage for the poorest billion. The Lancet, 396(10256),991-1044. https://doi.org/10.1016/S0140-6736(20)31907-3
12. Caquet, T., Gascuel, C., Tixier-Boichard, M. (2020). Agroecology: Research for the transition of agri-food systems and territories. 96 pp. Quae, Versailles, France. DOI 9782759232949.
13. Chaudhary, A., Gustafson, D., Mathys, A. (2018). Multi-indicator sustainability assessment of global food systems. Nature Communications, 9(1), 1-13.
14. Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S., von Maltitz, G. (Eds.). (2018) World Atlas of Desertification. Publication Office of the European Union, Luxembourg.
15. Committee on World Food Security (CFS) (2021). About the CFS. CFS, Rome. http://www.fao.org/cfs/home/about/en/ (accessed online March 14, 2021).
16. Committee on World Food Security (CFS). (2020). CFS Voluntary Guidelines on Food Systems for Nutrition (VGFSyN). Draft for Negotiations. CFS, Rome. http://www.fao.org/fileadmin/templates/cfs/Docs1920/Nutrition_Food_System/CFS_Voluntary_Guidelines_Food_Systems_Nutrition_Draft_for_Negotiations_16Mar.pdf.
17. Cotula, L., Oya, C., Codjoe, E. A., Eid, A., Kakraba-Ampeh, M., Keeley, J., Asare, R. O. (2014). Testing claims about large land deals in Africa: Findings from a multi-country study. Journal of Development Studies, 50(7), 903-925.
18. Crews, T. E., & Cattani, D. J. (2018). Strategies, Advances, and Challenges in Breeding Perennial Grain Crops. Sustainability, 10(7), 1-7.
19. Deng, X., den Bakker, H.C., Hendriksen, R.S. (2016). Genomic epidemiology: whole-genome-sequencing–powered surveillance and outbreak investigation of foodborne bacterial pathogens. Annual Review of Food Science and Technology, 7, 353-374.
20. Devleesschauwer, B., Haagsma, J.A., Mangen, MJ.J., Lake, R.J., Havelaar, A.H. (2018) The Global Burden of Foodborne Disease. In: Roberts T. (Ed) Food Safety Economics. Food Microbiology and Food Safety. Springer, Cham. https://doi.org/10.1007/978-3-319-92138-9_7.
21. De Schutte, O. (2013). The Reform of the Committee on World Food Security: The Quest for Coherence in Global Governance. Centre de philosophie du droit (CRIDHO), Working Paper 2013/8. Université catholique de Louvain, Louvain-la-Neuve.
22. Di Marco, M., Baker, M.L., Daszak, P., De Barro, P., Eskew, E.A., Godde, C.M., et al. (2020). Opinion: Sustainable development must account for pandemic risk. Proceedings of the National Academy of Sciences, 117(8), 3888-3892.
23. Donati, M., Menozzi, D., Zighetti, C., Rosi, A., Zinetti, A., Scazzina, F. (2016). Towards a sustainable diet combining economic, environmental and nutritional objectives. Appetite, 106, 48-57.

24. Drewnowski, A. (2005). Concept of a nutritious food: toward a nutrient density score. Am J Clin Nutr, 82:721-32.
25. Fanzo, J. (2019). Healthy and Sustainable Diets and Food Systems: The key to achieving Sustainable Development Goal 2? Food Ethics, 4, 159-174.
26. FAO. (2018). The Future of Food and Agriculture – Alternative pathways to 2050. Rome: FAO
27. FAO, IFAD, UNICEF, WFP and WHO. (2017). The State of Food Security and Nutrition in the World 2017. Rome: FAO
28. FAO, IFAD, UNICEF, WFP and WHO. (2020). The State of Food Security and Nutrition in the World 2020. Rome: FAO.
29. FAO. (2011). Global Food Losses and Food Waste: Extent, Causes and Prevention. Rome: FAO.
30. Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., et al. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342.
31. Fore, H., Dongyu, Q., Beasley, D., Ghebreyesus, T. (2020). Child malnutrition and COVID-19: the time to act is now. The Lancet, 396(10250), 517-518.
32. Frank, S., Havlík, P., Soussana, J.F., Levesque, A., Valin, H., Wollenberg, E., et al. (2017). Reducing greenhouse gas emissions in agriculture without compromising food security. Environmental Research Letters, 12(10), 105004.
33. Frison, E., & Clément, C. (2020). The potential of diversified agroecological systems to deliver healthy outcomes: Making the link between agriculture, food systems & health. Food Policy, 101851.
34. FSIN (Food Security Information Network). (2020). 2020 Global Report on Food Crises: Joint analysis for better decisions. Rome: FSIN.
35. Fuglie, K., Gautam, M., Goyal, A., Maloney,WF. (2020). Harvesting Prosperity: Technology and productivity growth in agriculture. Washington DC: World Bank. https://openknowledge.worldbank.org/handle/10986/32350.
36. GAIN (Global Alliance for Improved Nutrition). (2017). What constitutes a nutritious and safe food? Geneva: GAIN. Available from: https://www.gainhealth.org/sites/default/files/publications/documents/gain-nutritious-food-definition.pdf.
37. Gaupp, F., Hall, J., Hochrainer-Stigler, S., Dadson, S. (2020). Changing risks of simultaneous global breadbasket failure. Nature Climate Change, 10(1), 54-57.
38. Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., et al. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. Nature Sustainability, 3(3), 200-208.
39. Gillespie, S., van den Bold, M. (2017). Agriculture, food systems, and nutrition: meeting the challenge. Global Challenges, 1(3), 1600002.
40. Glover, JD., Reganold, JP., Bell, LW., Borevitz, J., Brummer, EC., Buckler, ES., Cox, CM., et al. (2020). Increased food and ecosystem security via perennial grains. Science 328(5986): 1638-1639.
41. GNR (Global Nutrition Report). (2020). 2020 Global Nutrition Report: Action on equity to end malnutrition. Bristol, UK: Development Initiatives.
42. Gosling, S.N., & Arnell, N.W. (2016). A global assessment of the impact of climate change on water scarcity. Climatic Change, 134(3), 371-385.
43. Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., et al. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change, 8(8), 699-703.
44. Hawkes, C., Ruel, M.T., Salm, L., Sinclaire, B., Branca, F. (2019). Double-duty actions: seizing programme and policy opportunities to address malnutrition in all its forms. The Lancet volume 395, issue 10218, p142-155. DOI:https://doi.org/10.1016/S0140-6736(19)32506-1
45. Headey, D., Alderman, H. (2019). The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. The Journal of Nutrition, 149(11), 2022-2033.
46. Headey, D., Heidkamp, R., Osendorp, S., Ruel, M., Scott, N., Flory, A et al. (2020). Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. The Lancet, 396, 519-521.
47. Herrero, M., Hugas, M., Lele, U,. Wira, M., Torero, M. (2021). Shift to Healthy and Sustainable Consumption Patterns. A paper from the Scientific Group of the UN Food Systems Summit. UN, New York.
48. Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S., Hristov, A.N., Gerber, P., Gill, M. (2016). Greenhouse gas mitigation potentials in the livestock sector. Nature Climate Change, 6, no 5 452 61.
49. Herrero, M., Thornton, P. K., Power, B., Bogard, J. R., Remans, R., Fritz, S., et al. (2017). Farming and the geography of nutrient production for human use: a transdisciplinary analysis. The Lancet Planetary Health, 1(1), e33-e42.
50. Hertel, T.W., Ramankutty, N., Baldos, U.L.C. (2014). Global market integration increases the likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. Proceedings of the National Academy of Sciences 111: 13799-13804.

51. HLPE. (2020). Food security and nutrition: building a global narrative towards 2030. Rome: HLPE.
52. HLPE. (2014). Sustainable fisheries and aquaculture for food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.
53. Hodson, E., Niggli, U., Kaoru, K., Lal, R., Sadoff, C. (2021). Boost Nature Positive Production at Sufficient Scale - A paper on Action Track 3. A paper from the Scientific Group of the UN Food Systems Summit. UN, New York.
54. INFOSAN (2019). INFOSAN activity report 2018-2019. Geneva: World Health Organization and Food and Agriculture Organization of the United Nations; 2020. https://www.who.int/publications/i/item/9789240006928.
55. IPPC, 2019. Climate change and land, an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, IPPC, www.ipcc.ch/report/srcc.
56. Katz, D.L., Doughty, K., Njike, V., Treu, J.A., Reynolds, J., Walker, J., Smith, E., Katz, C. (2011). A cost comparison of more and less nutritious food choices in US supermarkets. Public Health Nutrition 14(9), 1693-1699.
57. Jaffee S., Henson S., Unnevehr L., Grace D., Cassou E. (2019). The safe food imperative: accelerating progress in low- and middle-income countries. Washington DC: International Bank for Reconstruction and Development and the World Bank. (https://openknowledge.worldbank.org/handle/10986/30568, accessed 4 February 2020).
58. Jarmul, S., Dangour, A.D., Green, R., Liew, Z., Haines, A., Scheelbeek, P. (2020). Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets'. Environ. Res. Lett. 15 (2020) 123014.
59. Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., et al. (2020). Global hunger and climate change adaptation through international trade. Nature Climate Change, 10, 829-835.
60. Kamilaris, A., Fonts, A., & Prenafeta-Boldύ, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. Trends in Food Science & Technology, 91, 640-652.
61. Madhu, K., Zilberman, D. (2012). Modeling the land-use and greenhouse-gas implications of biofuels. Climate Change Economics 3, no. 03 (2012): 1250016.
62. Khatodia, S., Bhatotia, K., Passricha, N., Khurana, S.M.P., Tuteja, N. (2016). The CRISPR/Cas genome-editing tool: application in improvement of crops. Frontiers in plant science, 7, 506.
63. Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, Aet al. (2014). Increasing homogeneity in global food supplies and the implications for food security. Proceedings of the National Academy of Sciences, 111(11), 4001-4006.
64. Knapp, S., van der Heijden, M.G. (2018). A global meta-analysis of yield stability in organic and conservation agriculture. Nature communications, 9(1), 1-9.
65. Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J. (2012). Lost Food, Wasted Resources: Global Food Supply Chain Losses and Their Impacts on Freshwater, Cropland, and Fertiliser Use. Science of the Total Environment, 438: 477-89.
66. Laborde, D., Martin, W., Swinnen, J., Vos, R. (2020). COVID-19 risks to global food security. Science, 369(6503), 500-502.
67. Lawrence, D., Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. Nature climate change, 5(1), 27-36.
68. Lowder, S.K., Skoet, J., Raney, T. (2016). The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Development, 87, 16-29.
69. Lutz, W., & Samir, K. C. (2011). Global human capital: Integrating education and population. Science, 333(6042), 587-592.
70. MacDonald, G.K., Brauman, K.A., Sun, S., Carlson K.M., Cassidy, E.S., Gerber, J.S., West P.C. Rethinking Agricultural Trade Relationships in an Era of Globalization. BioScience, 65,(3), 275-289. https://doi.org/10.1093/biosci/biu225.
71. Maina, S., Kachrimanidou, V., Koutinas, A. (2017). A roadmap towards a circular and sustainable bioeconomy through waste valorization. Current Opinion in Green and Sustainable Chemistry, 8, 18-23.
72. Manners, R., van Etten, J. (2018). Are agricultural researchers working on the right crops to enable food and nutrition security under future climates? Global Environmental Change, 53, 182-194.
73. Masters, W.A., Bai, Y., Herforth, A., Sarpong, D.B., Mishili, F., Kinabo, J. Coates, J.C. (2018). Measuring the Affordability of Nutritious Diets in Africa: Price Indexes for Diet Diversity and the Cost of Nutrient Adequacy, American Journal of Agricultural Economics, 100(5), 1285-1301. https://doi.org/10.1093/ajae/aay059.

74. Mohanty, S.P., Hughes, D.P., & Salathé, M. (2016). Using deep learning for image-based plant disease detection. Frontiers in Plant Science, 7, 1419.
75. Mons, B., Neylon, C., Velterop, J., Dumontier, M., da Silva Santos, L.O.B., Wilkinson, M. D. (2017). Cloudy, increasingly FAIR: Revisiting the FAIR Data guiding principles for the European Open Science Cloud. Information Services & Use, 37(1), 49-56.
76. Martorell, R. (2017). Improved nutrition in the first 1000 days and adult human capital and health. Am J Hum Biol, 29 10.1002/ajhb.22952.
77. Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security, 14, 1-8.
78. NCD Risk Factor Collaboration. (2019). Rising rural body-mass index is the main driver of the global obesity epidemic in adults. Nature, 569(7755), 260.
79. Neufeld, L., Hendriks, S.L., Hugas, M. (2021). Healthy diet: A definition for the United Nations Food Systems Summit 2021. A paper from the Scientific Group of the UN Food Systems Summit. UN, New York.
80. Pellegrini, L., Tasciotti, L. (2014) Crop diversification, dietary diversity and agricultural income: empirical evidence from eight developing countries, Canadian Journal of Development Studies, 35:2, 211-227.
81. Perignon, M., Vieux, F., Soler, L., Masset, G., Darmon, N. (2017). Improving diet sustainability through evolution of food choices: Review of epidemiological studies on the environmental impact of diets. Nutrition Reviews, 75(1), 2-17.
82. Pretty, J., Benton, T.G., Bharucha, Z P., Dicks, L.V., Flora, C.B., Godfray, H.C. et al. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1(8), 441-446.
83. Quisumbing, A., Meinzen-Dick, R., Behrman, J., Basset, J. (2011) Gender and the global food-price crisis. Development in Practice, 21:4-5, 488-492.
84. Ruel, M.T., Quisumbing, A.R., & Balagamwala,M. (2018). Nutrition-sensitive agriculture: What have we learned so far? Global Food Security, 17, 128-153.
85. Samir, K.C., & Lutz, W. (2017). The human core of the shared socio-economic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change, 42, 181-192.
86. Scheelbeek, P., Bird, F. A., Tuomisto, H. L., Green, R., Harris, F. B., Joy, E., Chalabi, Z., Allen, E., Haines, A., & Dangour, A. D. (2018). Effect of environmental changes on vegetable and legume yields and nutritional quality. Proceedings of the National Academy of Sciences of the United States of America, 115(26), 6804-6809. https://doi.org/10.1073/pnas.1800442115.
87. Schmidt-Traub, G., Obersteiner, M., Mosnier, A. (2019). Fix the broken food system in three steps. Nature.com (comment) 569(7755):181-183.
88. Searchinger, T., Waite, R., Hanson, C., Ranganathan, J. (2018). Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050: A synthesis report. Washington DC: World Bank.
89. Shafiee-Jood, M., Cai, X. (2016). Reducing Food Loss and Waste to Enhance Food Security and Environmental Sustainability. Environmental Science & Technology, 50 (16), 8432-8443. DOI: 10.1021/acs.est.6b01993.
90. Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., et al. (2020). Which practices codeliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology, 26(3), 1532-1575.
91. Soussana, J.F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., et al. (2019). Matching policy and science: Rationale for the '4 per 1000-soils for food security and climate' initiative. Soil and Tillage Research, 188, 3-15.
92. Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., et al, P. (2018). Smarter metrics will help fix our food system. Nature, 558(7708), 7-8.
93. Tadele Z. (2019). Orphan crops: their importance and the urgency of improvement. Planta, 250, 677-694
94. Therond, O., Duru, M., Roger-Estrade, J., & Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. A review. Agronomy for Sustainable Development, 37(3), 21.
95. UNDRR. (2019), Global Assessment Report on Disaster Risk Reduction, Geneva, Switzerland, United Nations Office for Disaster Risk Reduction (UNDRR).
96. UN United Nations. (2021). Sustainable Development Goal 1: End poverty in all its forms everywhere. https://www.un.org/sustainabledevelopment/poverty/ Accessed 6 March 2021.
97. UNDESA United Nations Department of Economic and Social Affairs (2015). Population Facts. No 2015/1. https://www.un.org/esa/socdev/documents/youth/fact-sheets/YouthPOP.pdf

98. UNDESA United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Highlights (ST/ESA/SER.A/423).
99. UNICEF & WHO. 2019. UNICEF-WHO Joint Low Birthweight Estimates. [online]. [Cited 28 April 2020]. www.unicef.org/reports/UNICEF-WHO-lowbirthweight-
100. estimates-2019; www.who.int/nutrition/publications/UNICEF-WHO-lowbirthweight-estimates-2019.
101. UNICEF, WHO and the World Bank. (2020). Levels and Trends in Child Malnutrition: UNICEF / WHO / World Bank Group Joint Child Malnutrition Estimates. Geneva and Washington DC: UNICEF, WHO and the World Bank.
102. Valin, H., Sands, R D., Van der Mensbrugghe, D., Nelson, G.C., Ahammad, H., Blanc, E., et al. (2014). The future of food demand: Understanding differences in global economic models. Agricultural Economics, 45(1), 51-67.
103. van Vliet, J., Eitelberg, D.A., & Verburg, P.H. (2017). A global analysis of land take in cropland areas and production displacement from urbanisation. Global environmental change, 43, 107-115.
104. Von Braun, J., Afsana, K., Fresco, L., Hassan, M. and Torero, M. (2021). Food Systems – Definition, Concept and Application for the UN Food Systems Summit. A paper from the Scientific Group of the UN Food Systems Summit. UN, New York.
105. Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., et al. (2021). The 2020 report of The Lancet Countdown on health and climate change: Responding to converging crises. The Lancet, 397(10269):129-170.
106. WFP. (2017). World Food Assistance report 2017: Taking stock and looking ahead. Rome: WFP.
107. WFP (2020). COVID-19 will double number of people facing food crises unless swift action is taken. Retrieved from https://www.wfp.org/news/covid-19-will-double-number-people-facing-food-crises-unless-swift-action-taken.
108. WHO & UNICEF. (2017). The extension of the 2025 Maternal, Infant and Young Child nutrition targets to 2030. Discussion paper. . Geneva, Switzerland and New York: WHO & UNICEF.
109. WHO (2020). Dietary recommendations: Nutritional requirements; Establishing human nutrient requirements for worldwide application. WHO, Geneva. https://www.who.int/nutrition/topics/nutrecomm/en/
110. WHO. (2015a). WHO estimates of the global burden of foodborne diseases: foodborne disease burden. Geneva: WHO.
111. WHO. (2015b). World Report on Aging and Health. WHO, Geneva.
112. WHO (2013) Advancing food safety initiatives: strategic plan for food safety including foodborne zoonoses 2013-2022. Geneva: World Health Organization; 2013 https://apps.who.int/iris/bitstream/handle/10665/101542/9789241506281_eng.pdf;jsessionid=2CA0920F1CE46F365F5C65D9664C0A94?sequence=1
113. Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.J. (2017). Big data in smart farming–a review. Agricultural Systems, 153, 69-80.
114. World Bank, 2017. An investment framework for nutrition reaching the global targets for stunting, anemia, breastfeeding, and wasting. Washington, DC: World Bank Group.
115. World Bank (2018). Poverty and Shared Prosperity 2018: Piecing Together the Poverty Puzzle. Washington DC: World Bank.
116. World Food Programme. (2020). COVID-19 will double number of people facing food crises unless swift action is taken. https://www.wfp.org/news/covid-19-will-double-number-people-facing-food-crises-unless-swift-action-taken.
117. Wossen, T., Abdoulaye, T., Alene, A., Haile, M.G., Feleke, S., Olanrewaju, A., Manyong, V. (2017). Impacts of extension access and cooperative membership on technology adoption and household welfare. Journal of Rural Studies, 54, 223-233.
118. Xue L., G. Liu, J. Parfitt, et al. (2017). Missing food, missing data? A critical review of global food losses and food waste data. Environ. Sci. Technol., 51 (12), 6618-6633, 10.1021/acs.est.7b00401
119. Zilberman, D., Lu, L., Reardon, T. (2019). Innovation-induced food supply chain design. Food Policy 83: 289-297.
120. Zilberman, D. Fellows Address: The Economics of Sustainable Development. American Journal of Agricultural Economics 96, no. 2 (2014): 385-396.
121. Zuccala, E., Horton, R. (2020). Reframing the NCD agenda: a matter of justice and equity. The Lancet, 396(10256), 939-940. https://doi.org/10.1016/S0140-6736(20)31910-3.

This Report was prepared by members of the Scientific Group.

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

SHIFT TO HEALTHY AND SUSTAINABLE CONSUMPTION PATTERNS - A PAPER ON ACTION TRACK 2 -

by Mario Herrero, Marta Hugas, Uma Lele, Aman Wira, and Maximo Torero

ABSTRACT

Action Track 2 works to catalyse a shift in consumer behaviour that will create and build demand for sustainably produced agri- and ocean food products, strengthen shorter value chains, promote circular use of food resources, helping to reduce waste and improve nutrition, especially among the most vulnerable. This Action Track recognises that current food consumption patterns, often characterised by higher levels of food waste and a transition in diets towards higher energy, more resource-intensive foods, need to be transformed. Food systems in both developed and developing countries are changing

ABOUT THE AUTHORS

Mario Herrero Acosta (Costa Rica) Chief Research Scientist of Agriculture and Food, The Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Marta Hugas (Spain) Chief Scientist at European Food Safety Authority (EFSA).

Uma Lele (India) President of the International Association of Agricultural Economists (IAAE).

Aman Wirakartakusumah (Indonesia) Professor Em. at Department of Food Science and Technology and Senior Scientist at SEAFAST Center, Bogor Agricultural University (IPB), President-Elect of the International Union of Food Science and Technology.

Maximo Torero (Peru) ex-officio Member Chief Economist of the Food and Agriculture Organization of the United Nations (FAO).

rapidly. Increasingly characterised by a high degree of vertical integration, evolutions in food systems are being driven by new technologies that are changing production processes, distribution systems, marketing strategies, and the food products that people eat. These changes offer the opportunity for system-wide change in the way in which production interacts with the environment, giving greater attention to the ecosystem services offered by the food sector. However, developments in food systems also pose new challenges and controversies. Food system changes have responded to shifts in consumer preferences towards larger shares of more animal-sourced and processed foods in diets, raising concerns regarding the calorific and nutritional content of many food items. By increasing food availability, lowering prices and increasing quality standards, they have also induced greater food waste at the consumer end. In addition, the risk of fast transmission of food-borne disease, antimicrobial resistance and food-related health risks throughout the food chain has increased, and the ecological footprint of the global food system continues to grow in terms of energy, resource use, and impact on climate change. The negative consequences of food systems from a nutritional, environmental and livelihood perspective are increasingly being recognised by consumers in some regions. With growing consumer awareness, driven by concerns about the environmental and health impacts of investments and current supply chain technologies and practices, and by a desire among new generations of city dwellers to reconnect with their rural heritage and use their own behaviour to drive positive change, opportunities exist to define and establish added-value products that are capable of internalising social or environmental delivery within their price. These forces can be used to fundamentally reshape food systems by stimulating coordinated government action in changing the regulatory environment that in turn incentivises improved private sector investment decisions. Achieving healthy diets from sustainable food systems is complex and requires a multi-pronged approach. Actions necessary include awareness-raising, behaviour change interventions in food environments, food education, strengthened urban-rural linkages, improved product design, investments in food system innovations, public-private partnerships, public procurement, and separate collection enabling alternative uses of food waste can all contribute to this transition. Local and national policy-makers and small- and large-scale private sector actors have a key role in both responding to and shaping the market opportunities created by changing consumer demands.

Section 1. Introduction

There is global convergence on the need for transforming food systems so that they deliver nourishment, health for humanity while contributing to reducing the environmental pressures on our ecosystems. Transforming food systems involves five action tracks: AT1) access to safe and nutritious food, AT2) sustainable consumption, AT3) nature-positive production, AT4) equitable livelihood, and AT5) resilience to shocks and stress. As discussed by Action Track 1, we are not on track to meet international targets related to healthy diets. Currently, 690 million people are chronically malnourished, and two billion individuals suffer micronutrient deficiencies. Over consumption, notably of unhealthy dietary items, is rising rapidly. Two billion people are overweight or obese, with many suffering chronic diseases driven by poor dietary health (Development Initiatives, 2020; Global Panel on Agriculture and Food Systems for Nutrition, 2020). Food, our more proximate relationships to our physical health, is failing us. Globally, poor-quality diets are linked to 11 million deaths per year (Afshin et al., 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020).

As discussed by Action Track 1, we are failing the planet by enabling the food system to be the single largest driver of multiple environmental pressures. Food production accounts for 80% of land conversion and biodiversity loss including the collapse of major marine fisheries and freshwater ecosystems (Campbell et al., 2017; IPCC, 2019),high levels of contamination of freshwater and marine ecosystems (Mateo-Sagasta, Zadeh and Turral, 2017) ; accounts of 70% of freshwater withdrawals (Campbell et al., 2017), with major river systems such as the Colorado river in USA no longer reaching their deltas; and contributes approximately 30% of global greenhouse gas emissions (IPCC, 2019).

Action Track 2 recognises that current food usage patterns, often characterised by high levels of food loss and waste, a high prevalence of the consumption of diets high in energy, and the production of natural resource-intensive foods, need to be transformed to protect both people and the planet. At the same time, context is very important. The challenges and opportunities associated with a nutrient transition will vary for different contexts and countries, and will need to be evaluated and solved with an array of different solutions appropriate to their local conditions, culture and values. Awareness-raising, regulatory and behaviour change interventions in food environments, food education, strengthened urban-rural linkages, reformulation, improved product design, packaging and portion sizing, investments in food system innovations, public-private partnerships, public procurement, and separate collection enabling the reutilisation of food waste can all contribute to this transition. Local and national policy-makers and private sector actors of all sizes have a key role in both responding to and shaping the market opportunities created by changing consumer demands.

Section 2. Building the evidence on healthy diets

A healthy diet is health-promoting and disease-preventing. It provides adequacy without excess, of nutrients and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances (Healthy diet: A definition for the United Nations Food Systems Summit 2021). It must supply adequate calories for energy balance, and include a wide variety of high-quality and safe foods across a diversity of food groups to provide the various macronutrients, micronutrients and other food components needed to lead an active and healthy and enjoyable life.

Consumer demand, availability, affordability and accessibility are important drivers of dietary patterns. It is essential that these four aspects are considered simultaneously when pursuing dietary shifts (Global Panel on Agriculture and Food Systems for Nutrition, 2020). There is great diversity in the foods and culinary traditions of foods that together can form healthy diets, which vary widely across countries and cultures according to traditions, preferences and local food supplies. Food-based dietary guidelines translate these common principles into nationally or regionally relevant recommendations that consider these differences, as well as context-specific diet-related health challenges. National food-based dietary guidelines provide context-specific advice and principles on healthy diets and lifestyles, which are rooted on sound evidence, and respond to a country's public health and nutrition priorities, food production and consumption patterns, socio-cultural influences, food composition data, and accessibility, among other factors (http://www.fao.org/nutrition/education/food-dietary-guidelines/home/en/). Most food-based dietary guidelines recommend consuming a wide variety of food groups and diverse foods within food groups, plentiful fruits and vegetables, inclusion of starchy staples, animal-source foods and legumes, and limiting excessive fat, salt and sugars (Herforth et al., 2019; Springmann et al., 2020). However, there can be wide variation in inclusion of and recommendations for other foods. Only 17% of food-based dietary guidelines make specific recommendations about quantities of meat/egg/poultry/animal-sourced food to consume (20% make specific recommendations about fish), and only three countries (Finland, Sweden and Greece) make specific quantitative recommendations to limit red meat (Herforth et al., 2019). Only around one-quarter of food-based dietary guidelines recommend limiting consumption of ultra-processed foods, yet this is emerging as one of the most significant dietary challenges around the world.

Adherence with national food-based dietary guidelines and recommendations around the world is low. However, accurate data on actual consumption and its determinants is limiting, particularly for low- and low-middle-income countries (Lele, Goswami and Mekonnen, 2021). Recent estimates of consumption found the foods available for consumption did not meet a single dietary recommendation laid out in national food-based dietary guideline in 28% of countries, and the vast majority of countries (88%) met no more than two out of twelve dietary recommendations (Springmann et al., 2020). Dietary intake surveys show vast regional and national differences in consumption of the major food groups (Afshin et al., 2019). No regions globally have an average intake of fruits, whole grains, or nuts and seeds in line with recommendations and only central Asia meets the recommendations for vegetables. In contrast, the global (and several regional) average intake of red meat, processed meat and sugar-sweetened beverages exceeds recommended limits. Australasia and Latin America had the highest levels of red meat consumption, with high-income North America, high-income Asia Pacific and western Europe consuming the highest amount of processed meat (Afshin et al., 2019). In general, consumption of nutritious foods has been increasing over time, albeit likewise the consumption of foods high in fat, sugar, and salt, in a trend that is particularly evident as country incomes rise (Imamura et al., 2015). Of particular concern is the growing importance of highly processed foods and sugar-sweetened beverages in diets across the world. Sales of highly processed foods and sugar-sweetened beverages are about 10-fold higher in high-income compared to lower middle-income countries. However, sales growth is evident across all regions, the fastest occurring in middle-income countries (Baker et al., 2020).

Micronutrient dietary needs require consideration, especially for women of reproductive age, pregnant and lactating women, and children and adolescents. The odds of death in childbirth double with anaemia (Daru et al., 2018), a condition often caused by nutrient deficiency and affecting almost 470 million women of reproductive age and more than 1.6 billion people globally (WHO, 2008). Iron deficiency is estimated to cause 591,000 perinatal deaths and 115,000 maternal deaths per year (Stoltzfus, Mullany and Black, 2004), whereas undernutrition is an underlying cause of 45% of all deaths of children under the age of 5 years.

Animal-sourced foods can provide high-quality amino acid profile and micronutrient bioavailability. A recent study showed improved linear growth in children receiving animal-sourced foods vs cereal-based diets or no intervention (Eaton et al., 2019). Daily egg provision to young children have also shown increased linear growth compared to control (Iannotti et al., 2017). These changes in growth can be equated to larger economic gains across a nations, continents, and globally. A review of the association between stunting and adult economic potential found that a 1 cm increase in stature is associated with a 4% increase in wages for men and a 6% increase in wages for women (McGovern et al., 2017). The Cost of Hunger in Africa series has quantified the social and economist impact of hunger and malnutrition in 21 African countries and concluded that a) 8 to 44% of all child mortality is associated with undernutrition, b) between 1 to 18% of all school repetitions are associated with stunting, c) stunted children achieve 0.2 to 3.6 years less in school education, d) child mortality associated with undernutrition has reduced national workforces by 1 to 13.7%, and e) 40 to 67% of the working age population suffered from stunting as children (The Cost of Hunger in Africa series | World Food Programme, 2021). Furthermore, hunger and undernutrition have cost countries between 2 and 17% of their GDP (The Cost of Hunger in Africa series | World Food Programme, 2021).

Fish and fish products can be a key component of a healthy diet, given their nutrient-dense profile, including protein, omega-3 fatty acid and other micronutrients. In addition to the underconsumption of fruits, whole grains, nuts and seeds, as noted before, seafood is also generally eaten below recommended intake levels. With the exception of high-income Asia Pacific, seafood omega-3 fatty acids consumption is lower than optimal levels in all 21 global burden of disease regions. The recently-released the 2020-2025 Dietary Guidelines for Americans also notes that only 10% of Americans eat the recommended amount of seafood – two servings – each week.

Section 3. Building the evidence on healthy diets from sustainable food systems

First and foremost, we need evidence on actual food consumption to consider shifts to dietary patterns that promote all dimensions of individuals' health and well-being; have low levels of environmental pressure and impact; are accessible, safe and equitable; and are culturally acceptable (FAO & WHO, 2019). Considering current environmental challenges, transitioning to food systems that can enhance natural ecosystems, rather than simply sustaining them, may be desirable.

The conceptual transition from healthy diets to healthy diets from sustainable food systems was mediated by recent studies linking food availability patterns, and projections, to non-communicable disease health consequences, and the environmental impacts of food production (Tilman and Clark, 2014; Springmann, Wiebe, et al., 2018; Willett et al., 2019). A broad range of food availability patterns have been tested as alternatives to current food availability patterns, including Mediterranean, vegetarian, vegan, pescatarian, low animal products and many other variants (Aleksandrowicz et al., 2016; IPCC, 2019). The most recent set of studies is embodied in the work of the EAT-Lancet Commission on healthy diets from sustainable food systems (Willett et al., 2019). Healthy diets, based on food groups, were designed from a large body of evidence from nutrition observational studies. This helped to establish ranges of inclusion of different types of foods. It is important to note that these dietary recommendations diverge from most food-based dietary guidelines, and often have lower ranges of inclusion of animal-sourced foods, which have been the topic of significant debate, and therefore not widely accepted. The authors then used six environmental dimensions of importance to planetary health and earth system processes (greenhouse gas emissions, cropland use, water use, nitrogen and phosphorus use and biodiversity), using the planetary boundaries concept (Rockström et al., 2009), as boundary conditions for achieving a healthy diet from a sustainable food system. The environmental limits of food described by the EAT-Lancet Commission define a safe environmental space for food to help guide sustainable food consumption patterns.

Willett et al. (2019) found that flexitarian diets that allow for diversity of consumption options, including moderate meat consumption, would significantly reduce environmental impacts compared to baseline scenarios reflecting current consumption patterns. Flexitarian diets include the following characteristics:

1. high in diverse plant-based foods.
2. high in whole grains, legumes, nuts, vegetable and fruits consumption.
3. low in the consumption of animal-sourced foods (but requiring increases in fish consumption).
4. low in fats, sugars and discretionary/ultra-processed foods.

These diets can avert 10.8-11.6 million deaths per year from non-communicable diseases, a reduction of 19-24% from the baseline (consistent with the Global Burden of Disease studies). From an environmental perspective, transitions towards flexetarian patterns could contribute to reduce greenhouse gas emissions primarily, as a reduction in animal-sourced foods reduced land use and the numbers of animals, and their associated emissions. However, the increases in fruits, nuts and vegetables needed more land, water and fertilisers, and therefore increases in productivity of cereals and legumes to bridge yield gaps by close to 75%, and reductions in waste of 50% would be needed for achieving the diets within all sustainability constraints. These dynamics are consistent across many studies exploring dietary variants (Aleksandrowicz et al., 2016; Jarmul et al., 2020). However, the environmental footprint of foods is strongly dependent on where and how foods are produced, leaving significant room for innovation and improvement. Moreover, the adoption of any of the four alternative healthy diet patterns (flexitarian, pescatarian, vegetarian and the vegan diet) could potentially contribute to significant reductions of the social cost of greenhouse gas emissions, ranging from USD 0.8 to 1.3 trillion (50-74%) (FAO et al., 2020).

However, a limitation of plant-based diets is that they may not fulfil micronutrient needs, especially of the most vulnerable such as women of reproductive age, pregnant and lactating women, and children and adolescents. In contexts where diverse options for fortified cereals, grains, and foods are abundant, these outcomes demonstrate great potential for improving health and environmental indices because risk of undernutrition can be mitigated by the diversity of options in the food environment. In particular, biofortification of staple foods can lead to higher accessibility of micronutrients particularly to the poor and vulnerable. However, in contexts where such diversity of high-quality, fortified products is not abundant, the health risk to anaemia and iron deficiency due to a lack of vitamins and minerals is significant (as outlined above). The recommendations to move to more plant-based diets are complicated by the high quality of animal-sourced foods in terms of amino acid profile and micronutrient bioavailability and the evidence that the addition of such foods to plant-based diets of many populations could have large individual and societal benefits. Thus, when economic and socio-cultural sustainability are considered, as well as the complex landscape of diverse nutrition situations globally, healthy diets with sustainability consideration will look different in diverse contexts around the world

Transitions towards healthy diets, let alone sustainable consumption are critical contributors to achieving climate stability, and halting the rampant loss of biodiversity. Combined actions on securing habitat for biodiversity, improving production practices, and better consumption would allow for halting biodiversity loss and bending the curve towards restoration by 2030 (Leclere et al., 2020).

There is also a financial case for shifting to healthy diets from sustainable food systems. There are hidden costs of our dietary patterns and of the food systems supporting them and two of the most important are the health- and climate-related costs that the world incurs (FAO et al., 2020). If current food consumption trends continue, diet-related health costs linked to non-communicable diseases and their mortality are projected to exceed USD 1.3 trillion per year by 2030. On the other hand, shifting to healthy diets that include sustainability considerations would lead to an estimated reduction of up to 97% in direct and indirect health costs. The diet-related social cost of greenhouse gas emissions associated with current dietary patterns is projected to exceed USD 1.7 trillion per year by 2030. The adoption of healthy diets that include sustainability considerations would reduce the social cost of greenhouse gas emissions by an estimated 41-74% in 2030 (FAO et al., 2020).

Many studies (Springmann, Wiebe, et al., 2018; Swinburn et al., 2019; Willett et al., 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020; HLPE, 2020) discussing redirecting consumption recognise the need for different consumer behavioural shifts in different locations and contexts. For example, in low-income countries, achieving the healthy diet from sustainable food systems would require increasing the consumption of most nutrient-rich food groups, including animal-sourced foods, vegetables, pulses and fruits, while reducing some starches, oils and discretionary foods (Willett et al., 2019). In contrast, in many high-income countries achieving the same balance would require reducing the consumption of animal-sourced foods, sugars and discretionary/processed foods, while still increasing the consumption of healthy plant-based ingredients. For many countries, the transition will be complex and changes difficult to implement. The Global Nutrition Report 2020 demonstrated that of the 143 countries with comparable data, 124 have double or triple burden meaning that micronutrient deficiency is still prevalent in many developed countries demonstrating high levels of overweight/obesity (Development Initiatives, 2020). These countries would require these actions to play simultaneously in different population cohorts to achieve the desired benefits (Willett et al., 2019; Development Initiatives, 2020; HLPE, 2020), while a smaller number of countries (e.g. Japan) have smaller adjustments to make.

A global shift towards healthy diets from sustainable food systems will require significant transformations in food systems, and there is no one-size-fits-all solution for countries. Assessing context-specific barriers, managing short-term and long-term trade-offs and exploiting synergies will be critical. In countries where the food system also drives the rural economy, care must be taken to mitigate the potential negative impacts on incomes and livelihoods as food systems transform to deliver affordable healthy diets (FAO et al., 2020). Artificial intelligence may be able to assist in the transition to healthy diets from sustainable food systems. Examples of its application are in management and automation of crop and livestock production systems and the development of demand-driven supply chains. However, trade-offs and ethical considerations that arise from the use of artificial intelligence need to be carefully managed (Camaréna, 2020).

Fish and fish products have one of the most eco-efficient production profiles of all animal proteins. Ocean animals are more efficient than terrestrial systems in producing protein; their impact on climate change and land use is in general much lower than terrestrial animal proteins. One vital way to improve consumption of nutrient-rich and sustainable seafood is through aquaculture, the world's fastest growing food sector. According to the Global Panel on Agriculture and Food Systems for Nutrition (2021) "Aquaculture has real potential to accelerate economic growth, provide employment opportunities, improve food security, and deliver an environmentally sustainable source of good nutrition for millions of people, especially in low- and middle-income countries". The Ocean Panel also documented that the volume of food production from the ocean could be considerably increased. Under optimistic projections, the ocean could produce up to six times more food than it does today, and it could do so with a low environmental footprint.

Section 4. Transitioning to healthy diets from sustainable food systems

The evidence is abundantly clear that without shifts in consumption patterns towards health and sustainability we will fail to achieve multiple Sustainable Development Goals (SDGs), the Paris Climate Agreement, the post-2020 biodiversity goals, and we will lose the opportunity to reposition food to improve health and regenerate the environment. Achieving these transitions and managing the trade-offs and synergies will require additional attention to many facets of food systems, including:

Food environments: the consumption of healthy diets from sustainable food sources is dependent on sustainably produced healthy dietary items being available, affordable and accessible in different outlets. Whether they are in open markets in low- and middle-income countries, in supermarkets or in corner shops across the globe, or through bartering and sharing, the provisioning of nutritious food at affordable prices is a critical element for achieving transitions towards sustainable consumption (Downs, Loewenstein and Wisdom, 2009; Swinburn et al., 2019; FAO et al., 2020). These physical environments need to be developed to suit culture and tradition in different locations. Additionally, regulated advertisement and product placement will be essential for addressing positive behavioural changes (Swinburn et al., 2019). To increase consumption of healthy diets, the cost of nutritious foods must be affordable for all, although farmers must receive the real cost of growing food. The cost drivers of these diets are throughout the food supply chain, within the food environment, and in the political economy that shapes trade, public expenditure and investment policies (Swinburn et al., 2019; FAO et al., 2020).

Tackling these cost drivers will require large transformations in food systems at the producer, consumer, political economy, and food environments levels. Trade policies, mainly protectionary trade measures and input subsidy programmes, tend to protect and incentivise the domestic production of staple foods, such as rice and maize, often at the detriment of nutritious foods, like fruits and vegetables. International trade could certainly improve food systems resilience by spreading the risk of disruption in supply when not fully reliant on domestic production and/or trading with neighbouring countries. However, substantial imports from climate vulnerable countries by climate resilient trade partners could lead to a number of interlinked problems including a 'nutrient drain' of healthy dietary items away from production countries to countries with a much more diverse supply of foods, disrupting supply to importing countries when yields in production countries are affected by environmental influences (Scheelbeek et al., 2020). Non-tariff trade measures can help improve food safety, quality standards and the nutritional value of food, but they can also drive up the costs of trade and hence food prices, negatively affecting affordability of healthy diets (FAO et al., 2020). Nutrition-sensitive social protection policies, such as cash transfers, may assist the purchasing power and affordability of healthy diets of the most vulnerable populations.

Policies that more generally foster behavioural change towards healthy diets will also be needed. A critical challenge is the tremendous perishability of fruits and vegetables, particularly in tropical climates (Mason-D'Croz et al., 2019) where refrigeration, food processing and sustainable packaging may be critical contributions in creating environmental, and public health value. In both urban and rural areas, the lack of physical access to food markets, especially to fresh fruit and vegetable markets, represents a formidable barrier to accessing a healthy diet, especially for the poor. Finally, empowering all people and especially the poor and vulnerable with sufficient physical and human capital resources, assets and incomes is the necessary precondition to improve the access to healthy diets. This will enable making choices, produce and consume, leaving no one hungry or malnourished, while consuming healthy and nutritious food and preserve ecosystems, biodiversity and natural resources. However, making progress and achieving this objective entails dealing with all trade-offs, negative externalities and benefits emerging from policies and combination of policies presented previously.

Addressing food safety issues across value chains: Food safety is positioned at the intersection of agrifood systems and health, thereby there are very strong interconnections of bi-directional links between food safety, livelihoods, gender equity and nutrition disciplines (Grace et al., 2018).

Food safety across the value chains is to be ensured along all stages until consumption. Responsibilities lie with all actors from producers to processors, retailers and consumers. Consumer behaviour at households in storing (temperature) and handling foods (cross contamination) impacts strongly on the onset of foodborne intoxications. In the European Union, surveillance data indicate that most of the strong-evidence outbreaks in 2018 took place in a domestic setting (EFSA and ECDC, 2019). The safety of food is a matter of growing concern specially after the global estimation of the global burden of food-borne disease comparable to that of HIV/AIDS, malaria and tuberculosis together, with low- and middle-income countries bearing 98% of the global burden (WHO, 2015). Most of the known health burden comes from biological hazards (virus, bacteria, protozoa and worms), biological hazards cause acute intoxication which are easier to detect and control. Chronic effects due to chemicals (natural or processed contaminants, pesticide residues etc.) are more difficult to be traced and quantify their actual impact on the disease burden. The Global Burden of Foodborne Diseases report (WHO, 2015) quantified the burden of disease from aflatoxin, cassava cyanide and dioxins and other studies have estimated the burden for four food-borne metals (arsenic, cadmium, lead and methylmercury), which is substantial (Gibb et al., 2019). Since temperature and humidity are important parameters for the growth of fungi, climate change is anticipated to impact on the presence of mycotoxins in foods.

The riskiest foods for biological hazards are livestock products followed by fish, fresh vegetables and fruit (Grace et al., 2018). In addition to the disease burden, food-borne diseases in low- and middle-income countries also have a great impact on economic costs and market access (Unnevehr and Ronchi, 2014). In recent years, the possible impact of microplastics and nanoplastics on health via food has raised a lot of attention with multiple studies identifying the occurrence of micro and nanoplastic particles found in food commodities such as water, filtering molluscs and fish (Lusher, Hollman and Mendoza-Hill, 2017; Toussaint et al., 2019; van Raamsdonk et al., 2020). Currently, there is considerable effort to standardise the methods of analysis and identify the health impact from dietary exposure.

Food scares happen from time to time, with the following food incidents (real or perceived) causing a sudden disruption to the food supply chain and food consumption patterns with a high societal impact. In these situations, providing real-time information to consumers is very important so to keep the confidence in the food supply. Contaminant-based food scares relating to the use of antibiotics, hormones and pesticides have occurred in a number of food and drink sectors and appear to be of more concern to consumers compared to hygiene standards and food poisoning (Miles et al., 2004). Explicit investigations into the aforementioned food scares and their cumulative impact on food purchase behaviour could help further understanding of consumer responses to food scares (Knowles, Moody and McEachern, 2007).

There are many promising approaches to managing food safety in low- and middle-income countries but few have demonstrated an impact at scale. Food safety management systems are designed to prevent, reduce or eliminate hazards along the food chain, which includes primary production (farms), processors, retail distribution centres, supermarkets, and retail food outlets (Ricci et al., 2017). Food safety control at primary production is achieved using good general hygiene practices. Food business operators should implement and maintain permanent procedures based on the Hazard Analysis and Critical Control Points principles (WHO & FAO, 2006), which are effective in controlling most of the hazards during food production. Small-scale retail producers might have difficulties in Hazard Analysis and Critical Control Points due to complexity of some systems and lack of resources to implement and lack of access to information and appropriate education. Transitions to circular food systems, local food systems, or short circuit systems are often slowed or hampered by current food safety regulations. Ensuring food safety while enabling small-holder farmers, or craft food companies to operate in local contexts will be critical unlock in the transition to more sustainable food systems, and greater availability of healthy diets while supporting local economies.

To avoid confusion caused by multiple different national standards, the Food and Agriculture Organization of the United Nations and the World Health Organization established the Codex Alimentarius Commission to address safety and nutritional quality of foods and develop international standards to promote trade among countries (Codex Alimentarius Commission, 2007). The Codex Alimentarius establishes standards for maximum levels of food additives, maximum limits for contaminants and toxins, maximum residue limits for pesticides and veterinary drugs and gives indication for limits of microbiological hazards in a given food commodity. At national level, government food safety systems monitor compliance with official standards through food inspections. While metrics are considered key to monitoring and improving performance, they can also have unintended consequences, including focusing efforts on the thing to be measured rather than the ultimate goal of improving the thing being measured, stifling innovation through standardisation, costs that increase in disproportion to benefits attained, incentivising perverse behaviour to game metrics and reduced attention to things that are not measured (Bardach and Cabana, 2009), the balance and potential of large multinationals vs. small and medium-sized enterprises, short vs. long value chains, and low- and middle-income countries.

Even in higher income countries, small and medium-sized firms find it difficult to comply with complex and technocratic rules, measures and metrics that are characteristic of best practice food safety management systems and risk-based approaches: these methods are hardly applicable in low- and middle-income countries. The same applies for traceability, which appears only attainable in niche, high-value markets in low- and middle-income countries (Grace et al., 2018).

Local producers and value chains, income and land inequality: for many consumers, especially in low- and middle-income countries, local production is the main supplier of nutritious food (fruits, vegetables, pulses) and the primary provider of economic activity. Small and medium-sized farms produce critical nutrient diversity in rural areas (Herrero et al., 2017) and hence the transition to sustainable consumption requires support and value chain creation for linking food systems actors (HLPE, 2020).

As with any change, some people will be disadvantaged by the transition to healthy diets from sustainable food systems. It is important to provide support and transition options for potential losers impacted by the required changes to food systems (Herrero et al., 2020).

Many cities are playing more active roles in the development of city region food systems; notably recognising that environmental damage in areas within close proximity to cities impacts a large number of people, and that greater collaborations between cities and peri-urban spaces offers important opportunities to tackle environmental challenges while increasing the availability of healthy diets, and supporting stronger rural economies (e.g. the Paris Food System Strategy (Mairie de Paris, 2015)). Vertical farming could provide opportunities for increasing food production in urban areas (Al-Kodmany, 2018).

The role of trade in open and closed economies: Trade is an essential instrument in the food system, but it is not always geared towards sustainable consumption. While trade can act as an insurance policy to local disruptions, it can also increase exposure to disruptions in external markets. This is evident in many low- and middle-income countries where trade in cheaper, ultra-processed food with long shelf lives competes with healthy dietary items. In many regions around the world (i.e. the Pacific, South America) this is a likely contributing factor to high prevalence of obesity and increases in non-communicable diseases (Swinburn et al., 2019). However, trade also allows for leveraging of comparative advantages, which can allow production to be located where it is more efficient (Frank et al., 2018; IPCC, 2019). This has been a key feature of scenarios for achieving greenhouse gas mitigation targets (IPCC, 2019). However, when facing varied levels of regulation and power dynamics, trade can facilitate the outsourcing of environmental impacts of the food system to more vulnerable countries and individuals. Export-oriented value chains often are dominated by larger producers, who can concentrate market and political power as dominant producers and suppliers of food as well as sources of employment and revenue to governments (Swinburn et al., 2019). These aspects are intertwined with the political economy of food and need to be accounted for.

It is also important to consider the impacts of the rising number of barriers to international trade on the affordability of nutritious foods (including non-tariff measures put in place to ensure food safety), as restrictive trade policies tend to raise the cost of food, which can be particularly harmful to net food-importing countries (FAO et al., 2020). Protectionary trade measures such as import tariffs and subsidy programmes make it more profitable for farmers to produce rice or corn than fruits and vegetables. According to data from Tufts University, removing trade protection across Central America would reduce the cost of nutritious diets by as much as 9% on average (FAO et al., 2020). The efficiency of internal trade and marketing mechanisms is also important as these are key to reducing the cost of food to consumers and avoiding disincentives to the local production of nutritious foods.

The political economy of food: Swinburn et al. (2019) demonstrated that the current food system has large power imbalances and conflicts of interest when large commercial interests in food manufacturing and trade exist. While some large food companies are interested in opportunities for increasing their environmental sustainability, financial interests often prevail over sustainability concerns. Swinburn et al. (2019) articulates that changes in the regulatory environment and new incentives, combined with global efforts on sustainable trade, will be required to create the necessary accountability and shifts towards healthy diets.

Modifying behavioural changes: Most studies exploring the transitions towards healthy diets from sustainable food systems have focused on the technical feasibility of the diets and their production elements. Transition pathways and the levers for eliciting the required behavioural changes in consumption have received less attention (Garnett, 2016; HLPE, 2020).

Educating consumers to make healthy choices can modify behaviour in some cases. Educational campaigns in high-income countries have increased awareness and have also achieved some modest gains in fruit and vegetable consumption. However, most have not realised the target levels for consumption over the longer term (Brambila-Macias et al., 2011; Thomson and Ravia, 2011; Rekhy and McConchie, 2014). Certain people are more receptive to education on healthy diets than others. Providing nutritional information was found to change the behaviour of consumers already interested in nutrition but was unable to influence consumers with low interest in nutrition (Lone et al., 2009). Conversely, marketing incentives for healthy diets have been found to be more effective for people who have less healthy eating habits (Chan, Kwortnik and Wansink, 2017). Educational activities are more effective when used in in conjunction with environmental modifications, such as increasing the availability and accessibility of healthy dietary items(Van Cauwenberghe et al., 2010).

Altering food availability options can enhance healthy diets. A review of studies found strategic placement of fruit and vegetables could moderately increase fruit and/or vegetable choice, sales or servings (Broers et al., 2017). However, individual studies show mixed results. Furthermore, the provision of financial incentives to make healthy diets more affordable has been shown to increase consumption of fruits and vegetables (Olsho et al., 2016).

Taxes and front-of-pack information labels have been used with success to moderate the purchase of unhealthy dietary items, as well as influence reformulation of unhealthy products (Colchero et al., 2017; Roache and Gostin, 2017; Taillie et al., 2020). Although the magnitude of effect ranges, there is evidence that fiscal measures such as taxes on unhealthy dietary items improve diets (Andreyeva, Long and Brownell, 2010; Brambila-Macias et al., 2011; Eyles et al., 2012; Niebylski et al., 2015). A sugar-sweetened beverage tax has reduced consumption of sugar-sweetened in the study cohorts in Berkeley, USA (Lee et al., 2019) and Mexico (Sánchez-Romero et al., 2020). A review on the effect of subsidies for healthy dietary items and taxation on unhealthy dietary items found evidence that taxation and subsidy intervention influenced dietary behaviours to a moderate degree. The study suggests that food taxes and subsidies should be a minimum of 10 to 15% and should both be implemented to improve success and effect (Niebylski et al., 2015).

Reducing food loss and waste and embracing circularity: As discussed by Action Track 1 and 3, a critical component of rebalancing food systems is reducing food loss and waste. Food loss and waste currently accounts for significant losses of food availability around the world, and current estimates for food loss are 14% (FAO, 2019) and for food waste 17% (United Nations Environment Programme, 2021) of total production depending on the type of commodity. In low- and middle-income countries, these losses occur mostly at the pre-consumer stage due to harvest and storage losses while in OECD countries they are more significant at the consumption stage (for example, sell-by dates). Circular food systems have been suggested as a mechanism for reutilising these biomass streams (Jurgilevich et al., 2016). For example, it has been estimated that circular livestock could produce 7-23 g of protein per capita/day while decoupling livestock from land use systems (Van Zanten et al., 2018). Microbial protein production in fermentation processes or through alternative foods (i.e. insects, algae) are considered part of these solutions (Parodi et al., 2018; Pikaar et al., 2018).

Section 5. The key trade-offs and synergies

Food systems in low-, middle- and high-income countries are changing rapidly. Increasingly characterised by a high degree of vertical integration, high concentration, transitions in food systems are being driven by new technologies that are changing production processes, distribution systems, marketing strategies, and the food products that people eat (Stordalen and Fan, 2018; Herrero et al., 2020).

In terms of synergies, the arguments for aligned action on healthy diets from sustainable food systems are attractive from multiple standpoints. The possibility of engaging in triple-win actions linking health, consumption and the environment presents a real opportunity to achieve numerous global commitments simultaneously, which could be desirable from a policy perspective. These include planned emissions reductions (United Nations, 2015; IPCC, 2019; Leclere et al., 2020), reductions in malnutrition in all its forms and non-communicable diseases and achievement of SDG goals and targets (SDGs 1, 2, 3, 6, 8, 12-16). These multi-sectoral opportunities will require increased concerted action and alignment at global and national level. While potentially these synergies could lead to human and planetary well-being, their achievement could also yield significant trade-offs that will require resolution (Herrero et al., 2021). Some of these are related to the following dimensions:

Multiple environmental trade-offs: Changing consumption patterns can have impacts on the environmental footprints of the food system. Over a decade ago, Stehfest et al. (2009) demonstrated that reductions in the demand for animal-sourced foods could lead to reduced greenhouse gas emissions. These effects were mediated through reductions in methane production and carbon dioxide due to the use of less land and animals for achieving consumption targets. More recently, studies integrating many environmental indicators (Springmann, Clark, et al., 2018; Van Zanten et al., 2018; Willett et al., 2019) confirmed those findings, but due to the compositions of the healthy diets with higher amounts of coarse grains, fruits, vegetables and nuts, the environmental impact of these diets remains high. The impacts on different locations are markedly different due to different limiting constraints (i.e. water scarcity). It is only when consumption is modified, waste is reduced, and productivity increased that improvements across all environmental metrics are obtained.

Trade-offs with affordability and availability: A key trade-off of pursuing healthy diets from sustainable food systems is the increase in the costs of the diets in many countries, as a result of increasing the demand for nutrient-rich foods. Many people living in extreme poverty are the two billion who struggle to access sufficient foods and suffer acute caloric and nutrient deficiencies. Even the cheapest healthy diet costs 60% more than diets that only meet the requirements for essential nutrients. Examples like the EAT-Lancet diet are not affordable for an estimated 1.5 billion people (Hirvonen et al., 2020, Table 1) and almost double the cost of the nutrient adequate diet, and five times as much as diets that meet only the dietary energy needs through a starchy staple (FAO et al., 2020). This is of concern as the high cost and unaffordability of healthy diets is associated with increasing food insecurity and different forms of malnutrition, including child stunting and adult obesity. The unaffordability of healthy diets is due to their high cost relative to people's incomes. Healthy diets are unaffordable for more than 3 billion poor people in low-, middle- and high-income countries, and more than 1.5 billion people cannot even afford a diet that only meets required levels of essential nutrients (FAO et al., 2020; Global Panel on Agriculture and Food Systems for Nutrition, 2020). The cost of a healthy diet is much higher than the international poverty line, established at USD 1.90 purchasing power parity per day. At a global level, on average a healthy diet is not affordable, with the cost representing 119% of mean food expenditures per capita per day. Where hunger and food insecurity are greater, the cost of a healthy diet even exceeds average national food expenditures. The cost of a healthy diet exceeds average food expenditures in most countries in the Global South. More than 57% or more of the population throughout sub-Saharan Africa and Southern Asia cannot afford a healthy diet (FAO et al., 2020).

Part of the reason why many of the components of healthy diets are expensive follow the basic economics of supply and demand. In many cases, production of key dietary components does not meet the required demand, even at global level, and therefore their prices are high. Mason-D'Croz et al. (2019) recently demonstrated this for fruits and vegetables, a key component of healthy diets. The study concluded that even under optimistic socioeconomic scenarios, future supply will be insufficient to achieve recommended levels in many countries. Even where supply exists (i.e. India), internal barriers like poorly developed markets, increased incomes do not necessarily result in increased consumption of healthy diets (Fraval et al., 2019).

Low market access can be a large barrier to achieving a healthy diet. A 'food desert' refers to areas with poor access to a retail outlet with fresh produce, where cheap, ultra-processed, and unhealthy dietary items can predominate. While food deserts are often associated with economically disadvantaged communities in high-income countries (Walker, Keane and Burke, 2010; Ghosh-Dastidar et al., 2014), they also affect poor urban communities in low- and middle-income countries, particularly newly urban communities (Battersby and Crush, 2014). Food deserts can also be poor in areas that lack of refrigeration, have harsh environment conditions, or poor storage conditions, far from towns, where highly processed foods can be stored easily (i.e. the Pacific). Vertical farming may provide opportunities for food production in urban areas, where available land for farming is limited and expensive. Currently, economic feasibility, codes, regulations, and a lack of expertise are major obstacles to implementing the vertical farming (Al-Kodmany, 2018).

Trade-offs with pandemics and zoonosis: In contexts where animal-sourced food consumption is higher than recommended, shifting towards greater plant consumption would also have the added benefit of preserving ecological systems and wildlife and avoiding the spill over of zoonotic agents (mainly viruses) from wildlife to humans. In contexts where animal-sourced food consumption is critical for maintaining appropriate intake of essential nutrients, it is vitally important to scale up a ONE HEALTH approach that enables environmental, animal, and human health (Wood et al., 2012; Gale and Breed, 2013) causing a public health threat. In recent years there have been several examples of such spill overs (Ebola, SARS, MERS and COVID-19) with dramatic economic and public health consequences and the potential to cause global pandemics (see Box 1). A consequence of the COVID-19 pandemic is the disruption of global, or concentrated value chain production in terms of affordability and food availability; inversely, many of local value chains have seen increases in production and market shares.

The global burden of disease from food consumption is very different across the globe (WHO, 2015) and it is in a large part produced by zoonotic infections. Today, the largest food source attributions in food-borne intoxications is from food of animal origin in the developed world. Antimicrobial resistance contributes significantly to the burden of disease across the globe and constitutes a threat to public health.

Table 1 Number and share of people with daily income below the cost of the EAT-Lancet reference diet, by country income levels and major regions (Hirvonen et al. 2019)

	Number of countries	Population (in millions)	Share (%)
Global	141	1579·02	23·8%
By country income level			
High income	38	9·00	0·8%
Upper-middle income	37	254·07	10·8%
Lower-middle income	40	1005·89	37·1%
Low income	26	310·06	62·2%
By geographical region			
East Asia and Pacific	13	319·88	15·0%
Europe and central Asia	45	14·86	1·7%
Latin America and Caribbean	19	62·84	11·6%
Middle East and North Africa	11	48·40	19·4%
North America	2	3·95	1·2%
South Asia	7	627·31	38·4%
Sub-Saharan Africa	44	501·77	57·2%

We used the World Bank's PovcalNet system to calculate the share of people in each country whose daily consumption or income was less than the estimated cost of the EAT-Lancet reference diet.

Box 1. The impact of COVID19 on Food Systems

Food
The new type of respiratory tract disorder COVID-19 is based on an infection with the new type of coronavirus (SARS-CoV-2). The main target organs of coronaviruses in humans are the respiratory tract organs. The scientific data collected so far suggests that the virus is to be transmitted mainly via small respiratory droplets through sneezing, coughing, or when people interact with each other in close proximity, as it may happen in slaughterhouses and meat processing plants, where environmental conditions seem more favourable than in other places to the propagation of the virus. In fact, there have been COVID-19-related outbreaks at some slaughterhouses and meat processing plants worldwide, which has led to risk management measures to contain the propagation of the virus from occupational exposure among workers and related communities. Up to now, there is no evidence that food, including meat, is a source or transmission route of SARS-CoV-2. Meat, like any other food, might theoretically be contaminated by SARS-CoV-2. This could happen with food in the same way that it could happen with any other animated or non-animated surface. For example, food might be exposed to the virus through contamination by an infected person during food manipulation and preparation. This does not mean however that the food ingested would cause infection on the consumer. As indicated above, there is so far no evidence of transmission of this virus through ingestion of any type of food. Several food safety agencies and organisations worldwide concluded that there is no evidence of food-borne transmission of the virus.

Pandemics and value chains
COVID19 is an example of the importance of ONE HEALTH approach as it is a zoonosis (disease transmitted from animals to humans). It is well known that damaging ecological systems might lead to spill overs of zoonotic agents (mainly viruses such as Ebola, SARS, MERS) outside their original environment with dramatic economic and public health consequences and the potential to cause global pandemics. A consequence of the COVID-19 pandemic is the disruption of global, or concentrated value-chain production in terms of affordability and food availability; inversely, many of local value chains have seen increases in production and market shares.

Waste
In response to COVID-19, hospitals, healthcare facilities and individuals are producing more waste than usual, including masks, gloves, gowns, other protective equipment and single use plastics that could be infected with the virus. Infected medical waste could lead to public health risks, as well as environmental risks adding as to land, riverine and marine pollution.

Political economy trade-offs: Broad awareness of the positive or negative consequence of food systems changes from a nutritional, health, environmental and livelihood perspectives among key policy-makers is key to policy changes that facilitate a transition to healthy diets from sustainable food systems. Increased biodiverse agricultural production can result in increased employment and income, leading to growing demand for (healthy) food, provided that there is strong consumer awareness regarding diets and their consequences, and provided that there are few competing demands on the incomes, especially of the poor.

The political impediments to achieving healthy and sustainable diets are numerous. Maintaining the status quo benefits the current actors of the food system, hence the inertia for change (Béné et al., 2020; Fanzo et al., 2020; Herrero et al., 2020). Additionally, many public policies are not geared towards creating sustainable food systems, such as a lack of research and investment in nutritious foods at the expense of cereals or the creation of food environments that promote nutritious foods. The current system rewards economic efficiency rather than sustainability and the production of nutrition foods (Béné et al., 2020). Therefore, farmers have little incentives to change production practices. At the same time, large private companies have a disproportionate control on the food agenda, and this is not necessarily aligned with a health and sustainability agenda needed to transform the food systems.

Technology will be important, but even with the best intentions, ensuring that equitable and fair distribution of its availability and impacts are taken into account when designing transition pathways remains elusive (Herrero et al., 2021). Critical dialogues and transparency to design these transition pathways must be developed with a broad range of stakeholders, and values and motivations equally respected (Herrero et al., 2021).

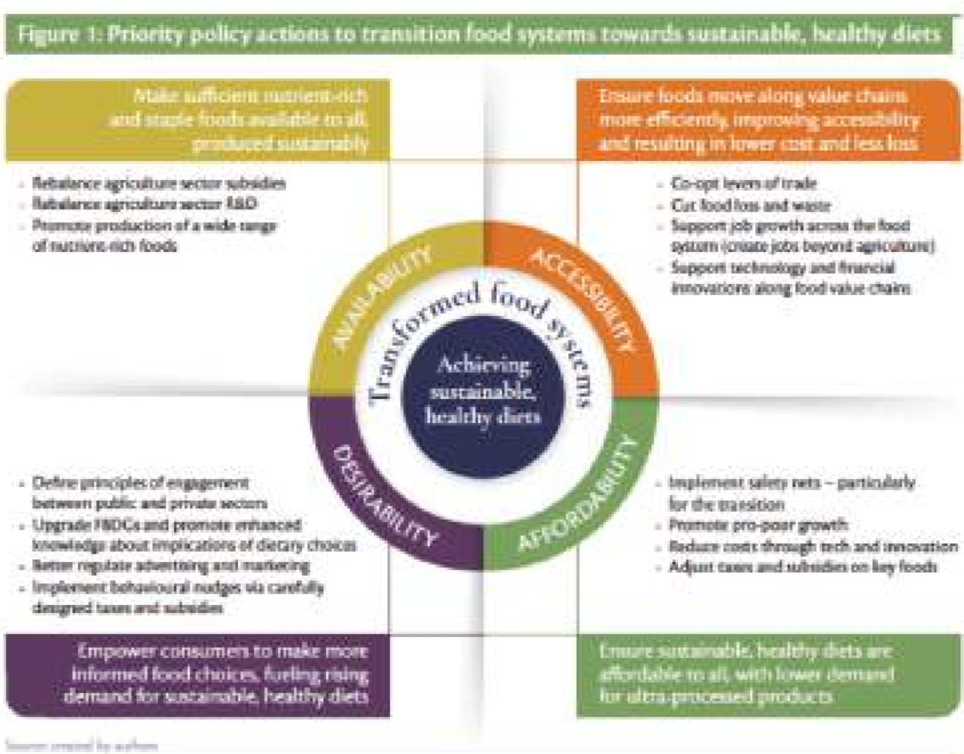
Section 6. Solutions and actions

Solutions to enable the shift towards more sustainable consumption need to be defined around cross-cutting levers connecting policy reform, coordinated investment, accessible financing, innovation, traditional knowledge, governance, data and evidence, and empowerment (Béné et al., 2020). It is important to identify and learn from the success stories of individuals and groups that have shifted to healthy diets from sustainable food systems and use these examples to clearly inform policy-makers, practitioners and the public. Figure 1, from the Global Panel on Agriculture and Food Systems for Nutrition (2020), synthesises the range of critical actions necessary to effectively create transition towards healthy and sustainable diets. We develop this list further into a broader set of actions for implementation in different contexts, which are presented below, following the categories of actions in Béné et al. (2020).

Economic and structural costs: Off-set the economic and structural costs associated with the transition to more healthy and sustainable diets.

- Policies and investments across food supply chains (food storage, road infrastructure, food preservation capacity, etc) are critical to cut losses and enhance efficiencies to reduce the cost of nutritious food (FAO et al., 2020).
- Provide support and transition options for potential losers impacted by the required changes to land use, food production practices, storage and processing technologies, food environment, distribution and food waste.
- Direct funding towards a healthy and sustainable food system, e.g. repurpose funding from monoculture crops, or foods which when overproduced are detrimental to health and environment (e.g. sugar and its derivatives).
- Facilitate easier access to loans from financial institutions, or lands from municipalities notably for young farmers, both men and women.
- Piloting and scaling behaviour change interventions that are effective in reducing consumer food waste and increasing adoption of healthy and sustainable diets.
- Investing in innovative food-related infrastructure and logistical systems that will improve the efficiency of food supply chains, particularly to urban consumers.
- In low and lower middle-income countries, facilitate increased consumption of nutrition foods by

Figure 1 Priority policy actions to transition food systems towards sustainable, healthy diets (Global Panel on Agriculture and Food Systems for Nutrition, 2020).



encouraging those with access to land to grow more nutritious themselves or by exchange within the local communities.
- Encourage creation of rural food markets in cities based on production and sale of indigenous and sustainably produced foods grown by local farmers.
- Break existing policy silos to facilitate food system transformations, providing support for a major policy drive to enhance the cultivation of indigenous food systems. Many native foods have biological components that can contribute to nutritionally-rich and healthy diet. Priority actions should be taken to promote research into these native foods worldwide.

Challenge the current political economy
- Encourage large food system actors to transition to the provision of healthy diets through incentives matched with penalisation or taxes for overproduction of unhealthy dietary items, or the use of degradative production practices.
- Trade policies and input subsidy programmes need to change incentives towards nutritious foods like fruits and vegetables. This also imply improvement of food safety to reduce non-tariff trade measures to increase the availability of healthy diets.
- Promote social and environmental aspects of corporate performance to be equal to financial performance.
- Regulatory measures such as taxes and front-of-pack information labels to limit the sale and production of unhealthy products.
- Change the global regulatory environment, including international trade and investment agreements to favour healthy diets from sustainable food systems.
- Promote divestment to avoid harm. This includes exclusion of certain companies from investment portfolios.
- Encourage a culture of corporate responsibility in the food industry to investigate the level of sustainability of products. Encourage social impact investing. This aims to generate positive social impact from investment decisions alongside financial return.
- Empower consumers to demand for healthy, sustainable products and reject unhealthy products.
- Encourage consumers to demand increased accountability for large food system actors.
- Institutions, for example schools, health care facilities as well as government offices can transition to healthier diets through improved nutrition standards which flow on to improve the nutritional quality of meals served in those institutions (Gearan and Fox, 2020).
- Gear public policies towards creating healthy diets from sustainable food systems.

Influencing consumer demand: The Global Panel on Agriculture and Food Systems for Nutrition, (2020) recommends the following four priority lines of action, also acknowledging that much better evidence of what works in low- and middle-income countries is required:
- Define principles of engagement between public and private sectors, leading to leveraging expertise and resources and influence of the businesses in the food sector. This recognises the considerable role of firms in driving consumer choices, too often in ways that are not conducive to healthy diets from sustainable food systems. A new relationship between public and private actors is needed, so that they can work together on a common agenda.
- Upgrade and improve food-based dietary guidelines and promote enhanced knowledge about implication of dietary choices. For example, food-based dietary guidelines seldom take account of issues of food system sustainability. Moreover, policy-makers in many governments need to take account of food-based dietary guidelines in developing policies, both in relation to the food system and in wider areas of government (e.g. relating to infrastructure development, safety nets, etc.).
- Improve regulation of advertising and marketing. This is mentioned in the AT2 paper and is discussed further in the Foresight report, which discusses, in particular, the ineffectiveness of businesses self-regulating.
- Implement behavioural nudges via carefully designed taxes and subsidises.

Education and cultural norms: The role of education will be pivotal in changing consumption patterns at many levels. It can facilitate a cultural shift in consumer perceptions and behaviour.
- Provide education and clarity for consumers about what constitutes a healthy and sustainable diet and educate consumers to make healthy choices and couple with other incentives to improve success and effect.
- Investing in women's, minorities and youth leadership and technical and managerial skills is key to promoting more equitable and sustainable participation of women in food supply chains, as producers, processors, business leaders and consumers, example of women's self-help groups.
- Alter food availability options to promote healthy diets.

- Invest in large-scale awareness-raising that connects food consumption patterns with health, environment and specifically climate change outcomes.
- Engage in school education programmes on healthy diets from sustainable food systems to ensure the next generation have a novel conceptualisation of what the food system can offer.
- Include sustainability of consumption learning modules in medical school curriculum worldwide.

Equity and social justice: Manage equity and social justice to provide the greatest benefit to all:

- Identify current consumption patterns of households.
- Encourage regions to transition to more healthy and sustainable diets in a culturally appropriate manner.
- The systematic use of full supply chain traceability has been shown to promote internal transparency (Bush et al., 2015). This could potentially be a way to promote social justice in the industry and protect people employed in low- and middle-income countries.
- Deploy safety nets to protect the poor against dynamic food systems transition that might render them vulnerable and disenfranchised. This will require international coherence and action (Global Panel on Agriculture and Food Systems for Nutrition, 2020).

Governance and decision support tools

- Invest in addition to knowledge, skills and data and tools needed to identify, prioritise and manage trade-offs and competing priorities.
- Establish standardisation and clear labelling.
- Develop tools for measuring consumer and retail food waste at national level, to understand the scale of the problem, identify hotspots for targeted action, and track progress towards SDG 12.3.
- Increased adherence to principles of circular economy recycling and repurposing food waste becomes the norm.
- Rationalising food-related sustainability standards. Such initiatives, which set standards for sustainable production and often include certification programmes to verify compliance, can be used as tools to drive consumer choice on the one hand and to channel and enhance the nascent demand for more sustainable food systems into market related investments on the other. However, some regulatory approaches and private sector-led schemes create barriers primarily because of the costs of compliance and the potential exclusion of actors. Nevertheless, some excellent example from the salmon industry exist(Global Salmon Institute, 2020).

Conclusions

A shift towards sustainable consumption patterns is necessary to harmonise global societal and environmental goals and for humanity to prosper sustainably and equitably in the coming years. Transitioning towards healthy diets from sustainable food systems at the country- level is essential to achieve this, together with strategies for managing waste reduction and increase productivity.

A range of constraints preventing this transition include lack of availability and access to healthy diets, costs of healthy, poor food environments, lack of incentives and standards, food safety, pandemics and in many cases political will. These are not insurmountable. Many strategies exist for circumventing these problems, including awareness-raising, behaviour change interventions in food environments, food education, strengthened urban-rural linkages, improved product design, investments in food system innovations, public-private partnerships, public procurement, and novel strategies for food waste management.

The role of science and innovation will be essential for deploying these interventions at scale and at low costs, and for minimising the potential trade-offs arising. Transparent multi-stakeholder dialogues will be key at all stages of planning the appropriate transition pathways towards our desired global goals of healthy diets, healthy ecosystems and prosperity for all.

REFERENCES

1. Afshin, A. et al. (2019) 'Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017', The Lancet, 393(10184), pp. 1958–1972. doi: 10.1016/S0140-6736(19)30041-8.
2. Al-Kodmany, K. (2018) 'The vertical farm: A review of developments and implications for the vertical city', Buildings, 8(2). doi: 10.3390/buildings8020024.
3. Aleksandrowicz, L. et al. (2016) 'The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review', PLOS ONE. Edited by A. S. Wiley, 11(11), p. e0165797. doi: 10.1371/journal.pone.0165797.
4. Andreyeva, T., Long, M. W. and Brownell, K. D. (2010) 'The impact of food prices on consumption: A systematic review of research on the price elasticity of demand for food', American Journal of Public Health. American Public Health Association, pp. 216–222. doi: 10.2105/AJPH.2008.151415.
5. Baker, P. et al. (2020) 'Ultra-processed foods and the nutrition transition: Global, regional and national trends, food systems transformations and political economy drivers', Obesity Reviews, (February), pp. 1–22. doi: 10.1111/obr.13126.
6. Bardach, N. S. and Cabana, M. D. (2009) 'The unintended consequences of quality improvement', Current Opinion in Pediatrics, 21(6), pp. 777–782. doi: 10.1097/MOP.0b013e3283329937.
7. Battersby, J. and Crush, J. (2014) 'Africa's Urban Food Deserts', Urban Forum, 25(2), pp. 143–151. doi: 10.1007/s12132-014-9225-5.
8. Béné, C. et al. (2020) 'Five priorities to operationalize the EAT–Lancet Commission report', Nature Food, 1(8), pp. 457–459. doi: 10.1038/s43016-020-0136-4.
9. Brambila-Macias, J. et al. (2011) 'Policy interventions to promote healthy eating: A review of what works, what does not, and what is promising', Food and Nutrition Bulletin, 32(4), pp. 365–375. doi: 10.1177/156482651103200408.
10. Broers, V. J. V. et al. (2017) 'A systematic review and meta-analysis of the effectiveness of nudging to increase fruit and vegetable choice', European Journal of Public Health, 27(5), pp. 912–920. doi: 10.1093/eurpub/ckx085.
11. Bush, S. R. et al. (2015) 'Sustainability governance of chains and networks: A review and future outlook', Journal of Cleaner Production, 107, pp. 8–19. doi: 10.1016/j.jclepro.2014.10.019.
12. Camaréna, S. (2020) 'Artificial intelligence in the design of the transitions to sustainable food systems', Journal of Cleaner Production. Elsevier Ltd, p. 122574. doi: 10.1016/j.jclepro.2020.122574.
13. Campbell, B. M. et al. (2017) 'Agriculture production as a major driver of the earth system exceeding planetary boundaries', Ecology and Society, 22(4). doi: 10.5751/ES-09595-220408.
14. Van Cauwenberghe, E. et al. (2010) 'Effectiveness of school-based interventions in Europe to promote healthy nutrition in children and adolescents: Systematic review of published and grey literature', British Journal of Nutrition, 103(6), pp. 781–797. doi: 10.1017/S0007114509993370.
15. Chan, E. K., Kwortnik, R. and Wansink, B. (2017) 'McHealthy', Cornell Hospitality Quarterly, 58(1), pp. 6–22. doi: 10.1177/1938965516668403.
16. Codex Alimentarius Commission (2007) Codex Alimentarius Commission: Procedural Manual. Rome: FAO &WHO. Available at: https://books.google.com.au/books?hl=en&lr=&id=P2zOGjHGoyIC&oi=fnd&pg=PA1&dq=Codex+Alimentarius+-Commission+2007&ots=aSg5DRv0sY&sig=R9DcaDIUKJRSI2IKEMno-jiNABg#v=onepage&q=Codex Alimentarius Commission 2007&f=false (Accessed: 4 November 2020).
17. Colchero, M. A. et al. (2017) 'In Mexico, evidence of sustained consumer response two years after implementing a sugar-sweetened beverage tax', Health Affairs, 36(3), pp. 564–571. doi: 10.1377/hlthaff.2016.1231.
18. Daru, J. et al. (2018) 'Risk of maternal mortality in women with severe anaemia during pregnancy and post partum: a multilevel analysis', The Lancet Global Health, 6(5), pp. e548–e554. doi: 10.1016/S2214-109X(18)30078-0.
19. Development Initiatives (2020) Global Nutrition Report, The Global Nutrition Report's Independent Expert Group. doi: 10.2499/9780896295841.
20. Downs, J. S., Loewenstein, G. and Wisdom, J. (2009) 'Strategies for promoting healthier food choices', in American Economic Review, pp. 159–164. doi: 10.1257/aer.99.2.159.
21. Eaton, J. C. et al. (2019) 'Effectiveness of provision of animal-source foods for supporting optimal growth and development in children 6 to 59 months of age', The Cochrane database of systematic reviews, 2(2), p. CD012818. doi: 10.1002/14651858.CD012818.pub2.
22. EFSA and ECDC (2019) 'The European Union One Health 2018 Zoonoses Report', EFSA Journal, 17(12). doi: 10.2903/j.efsa.2019.5926.
23. Eyles, H. et al. (2012) 'Food Pricing Strategies, Population Diets, and Non-Communicable Disease: A Systematic Review of Simulation Studies', PLoS Medicine. Edited by D. Stuckler, 9(12), p. e1001353. doi: 10.1371/journal.pmed.1001353.

24. Fanzo, J. et al. (2020) 'A research vision for food systems in the 2020s: Defying the status quo', Global Food Security, 26, p. 100397. doi: 10.1016/j.gfs.2020.100397.
25. FAO (2019) The State of Food and Agriculture. Rome, Italy. doi: 10.4324/9781315764788.
26. FAO et al. (2020) The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome. doi: 10.1109/JSTARS.2014.2300145.
27. FAO & WHO (2019) Sustainable healthy diets, Sustainable healthy diets. Rome. doi: 10.4060/ca6640en.
28. Frank, S. et al. (2018) 'Structural change as a key component for agricultural non-CO2 mitigation efforts', Nature Communications, 9(1), pp. 1–8. doi: 10.1038/s41467-018-03489-1.
29. Fraval, S. et al. (2019) 'Food Access Deficiencies in Sub-Saharan Africa: Prevalence and Implications for Agricultural Interventions', Frontiers in Sustainable Food Systems, 3(5), p. 104. doi: 10.3389/fsufs.2019.00104.
30. Gale, P. and Breed, A. C. (2013) 'Horizon Scanning for Emergence of New Viruses: From Constructing Complex Scenarios to Online Games', Transboundary and Emerging Diseases, 60(5), pp. 472–474. doi: 10.1111/j.1865-1682.2012.01356.x.
31. Garnett, T. (2016) 'Plating up solutions', Science, 353, pp. 1202–1204. doi: 10.1017/S1368980016000495.
32. Gearan, E. C. and Fox, M. K. (2020) 'Updated Nutrition Standards Have Significantly Improved the Nutritional Quality of School Lunches and Breakfasts', Journal of the Academy of Nutrition and Dietetics, 120(3), pp. 363–370. doi: 10.1016/j.jand.2019.10.022.
33. Ghosh-Dastidar, B. et al. (2014) 'Distance to store, food prices, and obesity in urban food deserts', American Journal of Preventive Medicine, 47(5), pp. 587–595. doi: 10.1016/j.amepre.2014.07.005.
34. Gibb, H. J. et al. (2019) 'Estimates of the 2015 global and regional disease burden from four foodborne metals – arsenic, cadmium, lead and methylmercury', Environmental Research, 174(December 2018), pp. 188–194. doi: 10.1016/j.envres.2018.12.062.
35. Global Panel on Agriculture and Food Systems for Nutrition (2020) Future Food Systems: For people, our planet, and prosperity.
36. Global Panel on Agriculture and Food Systems for Nutrition (2021) Harnessing aquaculture for healthy diets. London: UK.
37. Global Salmon Institute (2020) Sustainable salmon farming: the future of food.
38. Grace, D. et al. (2018) Food safety: Food safety metrics relevant to low and middle income countries, Food Safety. London.
39. Herforth, A. et al. (2019) 'A Global Review of Food-Based Dietary Guidelines', Advances in Nutrition, 10(4), pp. 590–605. doi: 10.1093/advances/nmy130.
40. Herrero, M. et al. (2017) 'Farming and the geography of nutrient production for human use: a transdisciplinary analysis', The Lancet Planetary Health, 1(1), pp. e33–e42. doi: 10.1016/S2542-5196(17)30007-4.
41. Herrero, M. et al. (2020) 'Innovation can accelerate the transition towards a sustainable food system', Nature Food, 1(5), pp. 266–272. doi: 10.1038/s43016-020-0074-1.
42. Herrero, M. et al. (2021) 'Articulating the effect of food systems innovation on the Sustainable Development Goals', The Lancet Planetary Health, 5(1), pp. e50–e62. doi: 10.1016/S2542-5196(20)30277-1.
43. Hirvonen, K. et al. (2020) 'Affordability of the EAT–Lancet reference diet: a global analysis', The Lancet Global Health, 8(1), pp. e59–e66. doi: 10.1016/S2214-109X(19)30447-4.
44. HLPE (2020) 'Food Security and Nutrition: Building a Global Narrative towards 2030', Research Guides. Available at: https://research.un.org/en/foodsecurity/key-un-bodies.
45. Iannotti, L. L. et al. (2017) 'Eggs in early complementary feeding and child growth: A randomized controlled trial', Pediatrics, 140(1), p. 20163459. doi: 10.1542/peds.2016-3459.
46. Imamura, F. et al. (2015) 'Dietary quality among men and women in 187 countries in 1990 and 2010: A systematic assessment', The Lancet Global Health, 3(3), pp. e132–e142. doi: 10.1016/S2214-109X(14)70381-X.
47. IPCC (2019) IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems: Summary for Policymakers, IPCC Special Report on Climate Change and Land. doi: 10.1002/9781118786352.wbieg0538.
48. Jarmul, S. et al. (2020) 'Climate change mitigation through dietary change: A systematic review of empirical and modelling studies on the environmental footprints and health effects of "sustainable diets"', Environmental Research Letters, 15(12), p. 123014. doi: 10.1088/1748-9326/abc2f7.
49. Jurgilevich, A. et al. (2016) 'Transition towards Circular Economy in the Food System', Sustainability, 8(1), p. 69. doi: 10.3390/su8010069.
50. Knowles, T., Moody, R. and McEachern, M. G. (2007) 'European food scares and their impact

on EU food policy', British Food Journal. Emerald Group Publishing Limited, pp. 43–67. doi: 10.1108/00070700710718507.
51. Leclere, D. et al. (2020) 'Bending the curve of terrestrial biodiversity needs an integrated strategy', Nature, pp. 1–6. doi: 10.1038/s41586-020-2705-y.
52. Lee, M. M. et al. (2019) 'Sugar-sweetened beverage consumption 3 years after the Berkeley, California, sugar-sweetened beverage tax', American Journal of Public Health. American Public Health Association Inc., pp. 637–639. doi: 10.2105/AJPH.2019.304971.
53. Lele, U., Goswami, S. and Mekonnen, M. M. (2021) 'Achieving Sustainable Healthy Food Systems: The Need for Actual Food Consumption Data for Measuring Food Insecurity and Its Consequences', Economic & Political Weekly, LVI(7), pp. 40–47.
54. Lone, T. A. et al. (2009) 'Marketing healthy food to the least interested consumers', Journal of Foodservice, 20(2), pp. 90–99. doi: 10.1111/j.1745-4506.2009.00131.x.
55. Lusher, A., Hollman, P. and Mendoza-Hill, J. (2017) Microplastics in fisheries and aquaculture: Status of knowledge on their occurrence and implications for aquatic organisms and food safety. Rome.
56. Mairie de Paris (2015) Sustainable Food Plan 2015-2020. Paris.
57. Mason-D'Croz, D. et al. (2019) 'Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study', The Lancet Planetary Health, 3(7), pp. e318–e329. doi: 10.1016/S2542-5196(19)30095-6.
58. Mateo-Sagasta, J., Zadeh, S. M. and Turral, H. (2017) Water pollution from agriculture: a global review Executive summary.
59. McGovern, M. E. et al. (2017) 'A review of the evidence linking child stunting to economic outcomes', International Journal of Epidemiology, 46(4), pp. 1171–1191. doi: 10.1093/ije/dyx017.
60. Miles, S. et al. (2004) 'Public worry about specific food safety issues', British Food Journal, 106(1), pp. 9–22. doi: 10.1108/00070700410515172.
61. Niebylski, M. L. et al. (2015) 'Healthy food subsidies and unhealthy food taxation: A systematic review of the evidence', Nutrition. Elsevier Inc., pp. 787–795. doi: 10.1016/j.nut.2014.12.010.
62. Olsho, L. E. et al. (2016) 'Financial incentives increase fruit and vegetable intake among Supplemental Nutrition Assistance Program participants: a randomized controlled trial of the USDA Healthy Incentives Pilot', The American Journal of Clinical Nutrition, 104(2), pp. 423–435. doi: 10.3945/ajcn.115.129320.
63. Parodi, A. et al. (2018) 'The potential of future foods for sustainable and healthy diets', Nature Sustainability, 1(12), pp. 782–789. doi: 10.1038/s41893-018-0189-7.
64. Pikaar, I. et al. (2018) 'Decoupling Livestock from Land Use through Industrial Feed Production Pathways', Environmental Science and Technology, 52(13), pp. 7351–7359. doi: 10.1021/acs.est.8b00216.
65. van Raamsdonk, L. W. D. et al. (2020) 'Current Insights into Monitoring, Bioaccumulation, and Potential Health Effects of Microplastics Present in the Food Chain', Foods, 9(1), pp. 1–28. doi: 10.3390/foods9010072.
66. Rekhy, R. and McConchie, R. (2014) 'Promoting consumption of fruit and vegetables for better health. Have campaigns delivered on the goals?', Appetite, 79, pp. 113–123. doi: 10.1016/j.appet.2014.04.012.
67. Ricci, A. et al. (2017) 'Hazard analysis approaches for certain small retail establishments in view of the application of their food safety management systems', EFSA Journal, 15(3). doi: 10.2903/j.efsa.2017.4697.
68. Roache, S. A. and Gostin, L. O. (2017) 'The untapped power of soda taxes: Incentivizing consumers, generating revenue, and altering corporate behavior', International Journal of Health Policy and Management. Kerman University of Medical Sciences, pp. 489–493. doi: 10.15171/ijhpm.2017.69.
69. Rockström, J. et al. (2009) 'A safe operating space for humanity', Nature. Nature Publishing Group, pp. 472–475. doi: 10.1038/461472a.
70. Sánchez-Romero, L. M. et al. (2020) 'Association between tax on sugar sweetened beverages and soft drink consumption in adults in Mexico: Open cohort longitudinal analysis of Health Workers Cohort Study', The BMJ, 369. doi: 10.1136/bmj.m1311.
71. Scheelbeek, P. et al. (2020) 'Health impacts and environmental footprints of diets that meet the Eatwell Guide recommendations: analyses of multiple UK studies', BMJ Open, 10, p. 37554. doi: 10.1136/bmjopen-2020-037554.
72. Springmann, M., Wiebe, K., et al. (2018) 'Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail', The Lancet Planetary Health, 2(10), pp. e451–e461. doi: 10.1016/S2542-5196(18)30206-7.
73. Springmann, M., Clark, M., et al. (2018) 'Options for keeping the food system within environmental limits', Nature, 562(7728), pp. 519–525. doi: 10.1038/s41586-018-0594-0.

74. Springmann, M. et al. (2020) 'The healthiness and sustainability of national and global food based dietary guidelines: Modelling study', The BMJ, 370, p. 2322. doi: 10.1136/bmj.m2322.
75. Stehfest, E. et al. (2009) 'Climate benefits of changing diet', Climatic Change, 95, pp. 83–102. doi: 10.1007/s10584-008-9534-6.
76. Stoltzfus, R. J., Mullany, L. and Black, R. E. (2004) 'Iron deficiency anaemia', in Comparative Quantification of Health Risks, pp. 163–210. doi: 10.1016/0957-5839(94)90009-4.
77. Stordalen, G. and Fan, S. (2018) 'Food security: The global food system under radical change', 2018 Global food policy report, pp. 14–19. doi: 10.2499/9780896292970_02.
78. Swinburn, B. A. et al. (2019) 'The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report', The Lancet, 6736(18), pp. 1–56. doi: 10.1016/S0140-6736(18)32822-8.
79. Taillie, L. S. et al. (2020) 'An evaluation of Chile's law of food labeling and advertising on sugar-sweetened beverage purchases from 2015 to 2017: A before-and-after study', PLoS Medicine, 17(2), p. e1003015. doi: 10.1371/JOURNAL.PMED.1003015.
80. The Cost of Hunger in Africa series | World Food Programme (2021). Available at: https://www.wfp.org/publications/cost-hunger-africa-series (Accessed: 24 March 2021).
81. Thomson, C. A. and Ravia, J. (2011) 'A Systematic Review of Behavioral Interventions to Promote Intake of Fruit and Vegetables', Journal of the American Dietetic Association, 111(10), pp. 1523–1535. doi: 10.1016/j.jada.2011.07.013.
82. Tilman, D. and Clark, M. (2014) 'Global diets link environmental sustainability and human health', Nature, 515(7528), pp. 518–522. doi: 10.1038/nature13959.
83. Toussaint, B. et al. (2019) 'Review of micro- and nanoplastic contamination in the food chain', Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment. Taylor and Francis Ltd., pp. 639–673. doi: 10.1080/19440049.2019.1583381.
84. United Nations (2015) Paris Agreement.
85. United Nations Environment Programme (2021) Food Waste Index Report 2021. Nairobi.
86. Unnevehr, L. J. and Ronchi, L. (2014) Food Safety and Developing Markets: Research Findings and Research Gaps, IFPRI Discussion Paper. Elsevier BV. doi: 10.2139/ssrn.2523530.
87. Walker, R. E., Keane, C. R. and Burke, J. G. (2010) 'Disparities and access to healthy food in the United States: A review of food deserts literature', Health and Place, 16(5), pp. 876–884. doi: 10.1016/j.healthplace.2010.04.013.
88. WHO (2008) 'Worldwide prevalence of anaemia 1993-2005'. Available at: http://whqlibdoc.who.int/publications/2008/9789241596657_eng.pdf.
89. WHO (2015) WHO Estimates of the Global Burden of Foodborne Disease, Foodborne disease burden epidemiology reference group 2007-2015. doi: 10.1007/978-3-642-27769-6_3884-1.
90. WHO & FAO (2006) Food and Agriculture Organization of the United Nations FAO/WHO guidance to governments on the application of HACCP in small and/or less-developed food businesses, WHO & FAO.
91. Willett, W. et al. (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', The Lancet, 393, pp. 447–492. doi: 10.1016/S0140-6736(18)31788-4.
92. Wood, J. L. N. et al. (2012) 'A framework for the study of zoonotic disease emergence and its drivers: Spillover of bat pathogens as a case study', Philosophical Transactions of the Royal Society B: Biological Sciences. Royal Society, pp. 2881–2892. doi: 10.1098/rstb.2012.0228.
93. Van Zanten, H. H. E. et al. (2018) 'Defining a land boundary for sustainable livestock consumption', Global Change Biology, 24(9), pp. 4185–4194. doi: 10.1111/gcb.14321.

This Report was prepared by members of the Scientific Group.

UNITED NATIONS
FOOD SYSTEMS
SUMMIT 2021
The Scientific Group for the
UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

ACHIEVING ZERO HUNGER BY 2030
A REVIEW OF QUANTITATIVE ASSESSMENTS OF SYNERGIES AND TRADE-OFFS AMONG THE UN SUSTAINABLE DEVELOPMENT GOALS

by Hugo Valin, Thomas Hertel, Benjamin Leon Bodirsky, Tomoko Hasegawa, Elke Stehfest

ABSTRACT

The Sustainable Development Goal 2 (SDG2) of "zero hunger" sets clear global targets for ensuring access to sufficient food and healthy nutrition for all by 2030, while keeping food systems within sustainable boundaries and protecting livelihoods. Nonetheless, the current trends show the level of challenge ahead, especially as the COVID-19 pandemic worsens the global development prospects. Intrinsically, SDG2 presents some points of tension between its internal targets and brings some synergies but also strong trade-offs with other SDGs.

In this paper, we summarize the main relations between SDG2 targets and the other development goals and ex-

ABOUT THE AUTHORS

Hugo Valin, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Thomas Hertel, Purdue University, West Lafayette, USA

Benjamin Leon Bodirsky, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

Tomoko Hasegawa, Ritsumeikan University, Kusatsu, Japan

Elke Stehfest, PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands

plain how the modeling literature has analyzed the SDG interactions around "Zero hunger". SDG2 integrates four ambitious objectives – adequate food, no malnutrition, in increased incomes for smallholders, greater sustainability – that will require careful implementation to be conducted in synergy. We show that the compatibility of these objectives will depend on the interplay of future food demand drivers and the contribution of productivity gains across the food system.

Analyzing the SDGs' interrelations reveals the strong synergies between SDG2 and some other basic subsistence goals, in particular Goal 1 "No poverty" and Goal 3 "Good health and well-being". These goals need to be jointly addressed to succeed on "Zero hunger". Several other SDGs have been shown to be key enablers for SDG2, in particular on the socioeconomic side. On the other hand, agricultural production substantially contributes to the risks of exceeding critical global sustainability thresholds. We illustrate how recent modeling work has shed light on the interface between future food and nutrition needs, and the various environmental dimensions. Specifically, several important SDGs have been shown to compete directly with SDG2 through their common demands for scarce natural resources, including land for climate (SDG13), biodiversity (SDG15) and cities (SDG11), as well as the provision of water, for both the environment and human needs (SDG6). Quantitative assessments show that more efficient production systems and technologies, pricing of externalities, and integrated resource management can mitigate some of these trade-offs, but are unlikely to succeed in resolving these altogether.

The success of achieving SDG2 in the face of these challenges will require new investments, smoothly functioning trade and effective markets, as well as changes in consumption patterns. Forward-looking analyses of global food systems indicate that deep transformations combining various measures will be needed to simultaneously achieve SDG2 targets while remaining within the planetary boundaries. These require fundamental changes, both on the supply side and on the demand side, and highlight the importance of SDG12 on "responsible production and consumption".

1. INTRODUCTION

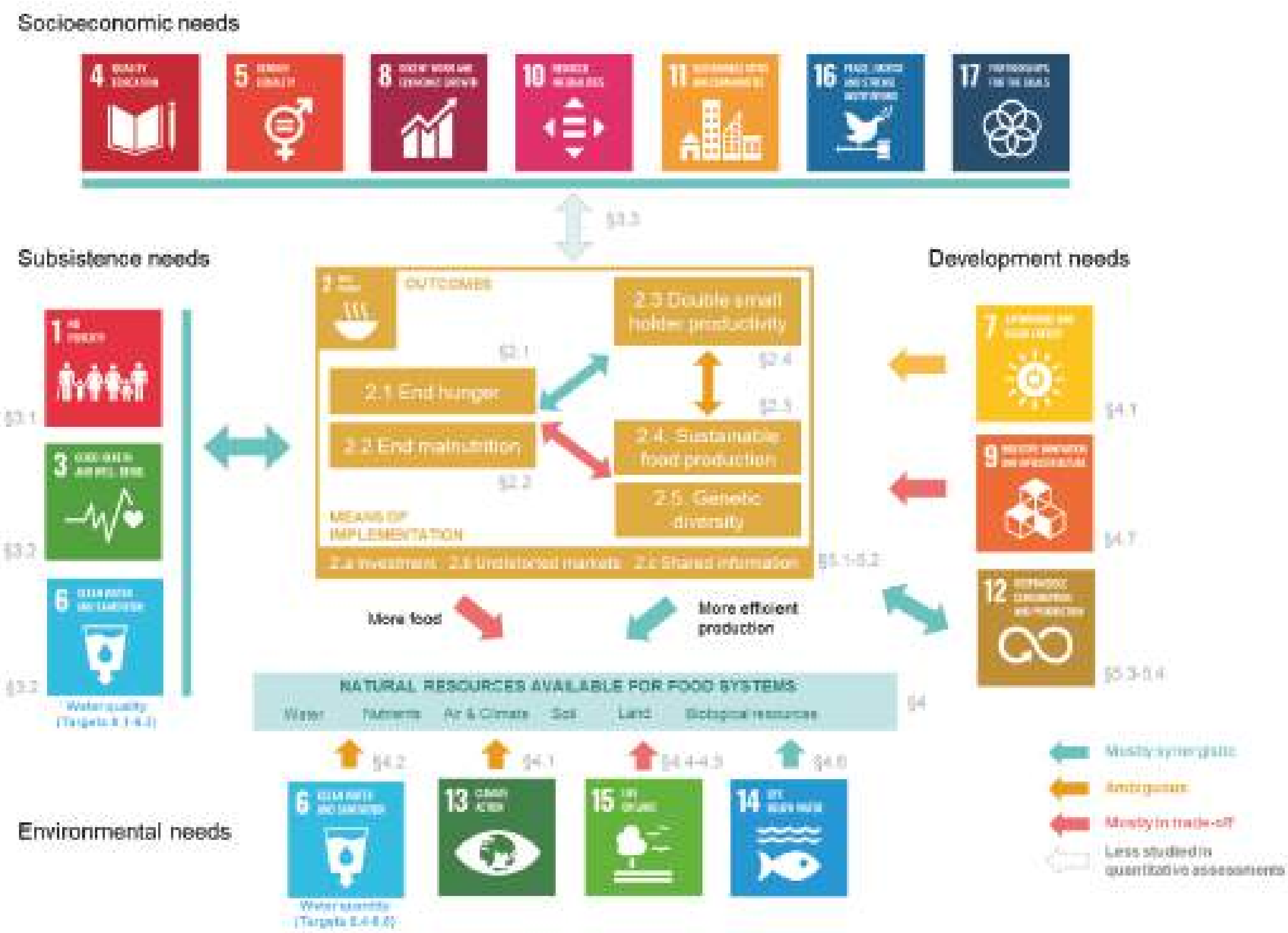
In 2015, 192 countries endorsed the United Nations 2030 Agenda for Sustainable Development, defining seventeen Sustainable Development Goals (SDGs) and associated targets to be reached over the next decade. SDG2 "Zero Hunger" represents a reinvigoration of the long-standing efforts by governments and international organizations to fight undernourishment and malnutrition across the globe. This battle is far from over, as 8.9% of the world population was still undernourished in 2019, 1.5 billion were unable to access essential food nutrients, and adult obesity now exceeds 13% globally (FAO et al., 2020), and at present the COVID-19 pandemic has increased food insecurity in many places around the world, due to the effect of sanitary measures and their socioeconomic consequences (Laborde et al., 2020; von Braun et al., 2020). At the same time, there has been increasing recognition that human activities, among which agriculture, spur large-scale environmental changes, driving us out of the Earth's safe operating space (Steffen et al., 2015). Therefore, the 2030 Agenda has integrated environmental sustainability into the core of the future development agenda (UN, 2015). The global food system modeling community has strived to better understand the synergies and trade-offs between these dimensions by quantifying the degree of compatibility of the different goals, to help identify the most efficient strategies and overcome the points of tensions between the SDGs.

This paper provides an overview of the state of findings from the global modeling literature on the potential avenues for achieving SDG2 and the interrelations between this objective and attainment of other SDGs, particularly those related to environmental sustainability (Figure 1). For the most part, it looks at these questions from a global, macroscopic perspective, without entering in detailed regional and local specificities, although recent efforts are seeking to better integrate cross-scale interconnections[1]. It complements in that sense previous analyses focusing on synergies and trade-offs from a conceptual point of view. For instance, the International Council for Science analyzed some of the most critical interfaces for SDG2 (ISC, 2017), emphasizing SDG1 (No poverty), SDG3 (Good health and well-being), SDG5 (Gender equality), SDG6 (Clean water and sanitation), SDG7 (Affordable and clean energy), SDG13 (Climate action) and SDG15 (Life on land). Pradhan et al. (2017) conducted a similar work across all of the SDG scope and identified relations mostly synergistic between SDG2 and SDG1-6, 10 and 17, mixed relations with SDG 7-9 and mostly conflictual relations with SDG 11-13 and 15.

1 See for instance AgMIP (www.agmip.org), FABLE (www.unsdsn.org/fable) or GLASSNET (https://mygeohub.org/groups/glassnet) initiatives.

Here, synergies and trade-offs between the achievement of SDG2 and the other SDG dimensions are examined based on the most recent modeling literature in the natural and social sciences. The work relies inter alia on large-scale forward-looking studies analyzing the evolution of the SDG2 target compared to other sustainability goals, at continental and global scales. Many of these studies adopt a medium- to long-term perspective, therefore our analysis will often look beyond 2030, and up to 2050. With Figure 1, we present our own depiction of how SDG2 interacts with other SDGs based on this literature. We identify many synergies with socioeconomic SDGs in general, while highlighting possible tensions the environmental SDGs. Not all of these dimensions have been explored with a similar level of depth by modeling studies. This is because quantitative models are stronger at analyzing some specific structural relations (e.g. macroeconomic indicators, environmental account balances) than some others (e.g. detailed social impacts, anthropometric indicators). For historical and technical reasons, some areas have also been relatively understudied (e.g. modeling malnutrition and obesity) compared to some others (e.g. climate change and food security). We provide more context in Box 1 on the different types of models used, and on their strengths and limitations.

Figure 1 SDG2, its targets and relations to other SDGs, as analyzed in this paper. Colored arrows represent direction and nature of main SDG relations (mostly synergistic or in trade-off). Relations less studies are marked with pale colors/dashed arrow outlines. References to specific sections of the paper addressing the various targets/goals and their interaction are in gray text (§X.X). SDG2 "Zero hunger" encompasses five outcome targets that can be summarized as follows: 2.1: ending hunger and ensure access to safe, nutritious and sufficient food, 2.2: ending all forms of malnutrition, 2.3: doubling agricultural productivity and income of small-scale food producers, 2.4: ensuring sustainable and resilient food production systems, and 2.5: maintaining the genetic diversity of farm assets. Not visualized here are the three "mean of implementation" targets defined to support the achievement of the outcomes above: 2.a: increasing investment in agriculture and rural development, 2.b: avoiding international trade restrictions and market distortions, 2.c: better collaborate for agricultural market functioning. See Appendix for full description or the UN official website at https://sdgs.un.org/goals/goal2.



The paper is structured as follows: in Section 2, we analyze in detail the inherent challenges of achieving SDG2. Section 3 focuses on the synergies between SDG2 and other SDGs, with an emphasis on the key companion goals – poverty and health – and the large set of socioeconomic enablers. Section 4 examines the trade-offs between SDG2 and other goals, looking at the food systems impacts and their mitigation, but also the reverse pressures from other objectives. We finally present in Section 6 an overview of possible food system transformation levers. These are key to the resolution of the trade-offs previously presented while setting the ground to more sustainable pathways for the coming decades.

Box 1. Modeling approaches for quantitative analysis of the global food system

A large set of modeling frameworks has been used to represent the global relations within the food system and its interactions with other socioeconomic and environmental components. These are rooted in different traditions: integrated assessment models of climate and environment (Parson and Fisher-Vanden, 1997), agricultural and trade models (Tongeren et al., 2001; von Lampe et al., 2014), computable general equilibrium models (Böhringer and Löschel, 2006; Hertel et al., 2009; Hertel et al., 2012), land system models (Foley et al., 1996; Haberl et al., 2007; Lotze-Campen et al., 2005), or household-level microsimulations (van Wijk et al., 2014). All of these frameworks have their own strengths and weaknesses and can also be combined to broaden the scope of their applications across domains or scales (van Wijk, 2014; Wicke et al., 2014).

As we will show below, these model families have been applied to a large set of topics related to the food systems and SDG interactions. Food security has been often approached under the availability angle in that literature (Baldos and Hertel, 2014; Gerten et al., 2020; Hasegawa et al., 2015; Valin et al., 2014; van Dijk et al., 2021), with substantial emphasis on the long-term food need prospects, the environmental impacts of food systems expansion and the threat of climate change. Aspects related to food access have been primarily considered through the effect of exogenous increase of income (Valin et al., 2014; Yu et al., 2004), or the effect of rising agricultural prices on consumers (Golub et al., 2012; Hasegawa et al., 2018; Nelson et al., 2014), while the favorable income effects of rising prices on people employed in agriculture have only been considered in CGE modeling and household simulations (Hallegatte and Rozenberg, 2017; Hertel et al., 2010). Efforts to explicitly model poverty and food access inequality reduction in IAMs to tackle food insecurity are more recent (Hasegawa et al., 2019; Soergel et al., 2021). Similarly, investigating food utilization is relatively new to that literature (van Meijl et al., 2020b). New emphasis on the question of stability and resilience is also now developing, both under the framing of extreme climate change events, and following the COVID-19 crisis (Swinnen and McDermott, 2020).

Drivers, scenarios, policy interventions and transformations.

Foresight studies have been a common way to approach the modeling of SDGs with these tools. They typically quantify the development of alternative scenarios over time and analyze the interplay of macro-level drivers and their impact on the long-term system trajectories. This approach is mainstream in the environmental (Millennium Ecosystem Assessment, 2005; OECD, 2012) and climate change domains (O'Neill et al., 2014; van Vuuren et al., 2011b) with the definition of archetype socioeconomic scenarios, such as the Shared Socioeconomic Pathways (SSPs), which are now applied to many other disciplines (O'Neill et al., 2020). These allow for discussion and assessment of a number of key uncertainties related to climate, demography and macroeconomics. In the case of agriculture and food systems, foresight analyses and scenario approaches have also been widely used (FAO, 2018; IAASTD, 2009; OECD, 2016; van Meijl et al., 2020a; von Lampe et al., 2014; Zurek et al., 2021). Many modeling analyses also focus on the impact of specific policy interventions (OECD and IIASA, 2020; Rosegrant et al., 2017; Stehfest et al., 2013), for which static analyses using equilibrium models are more common (Dixon and Parmenter, 1996; Hertel, 1997). These two approaches are currently on track to converge, as the policy interventions needed for attaining the SDGs are becoming increasingly relevant for analysis of system transformations to achieve sustainable pathways, as stressed by various recent initiatives (Food and Land Use Coalition, 2019; Sachs et al., 2019; Steiner et al., 2020) (see Section 5 and Table 1).

Strengths, limitations of models and possible improvements

Models are powerful tools to highlight structural tensions and interrelations between key variables in the food system in an integrated manner. As we illustrate in this paper, a large number of studies has assessed the economic and nutritional benefits of agricultural investments or the trade-offs with environmental domains. Much progress has been achieved through model comparisons in communities like the Agricultural Model Intercomparison and Improvement Project (AgMIP - Rosenzweig et al., 2013), the Integrated Assessment Model Consortium (IAMC - van Vuuren et al., 2011c), the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP - Warszawski et al., 2013) or the Global Trade Analysis Project (GTAP - Hertel, 2012a).

In spite of these efforts, several important limitations must be noted: i) the full set of malnutrition indicators remains underdeveloped in modeling approaches, and efforts in representing micro-nutrients and diet-related health burdens should be continued; ii) current models often lack sufficient granularity for accurate assessment of SDGs, with limited representation of heterogeneity across and within households, including gender-related one, or in the geographical details. Even though highly disaggregated approaches may bring difficulties, many new questions related to inequality of conditions and hotspots of impacts cannot be captured through aggregated representations; iii) the food system as a whole is often only partly or roughly represented. Aspects concerning the food environment, institutional, social and individual drivers are generally not well considered. Many models also do not represent the full supply chain from 'farm to fork', or only do so in an aggregated way, ignoring the role of economics of value chains, in particular for price transmission, and the political economy of food system actors (Barrett et al., 2019); iv) some important drivers of food security are difficult to model, such as the role of conflicts or institution and governance. These elements are often captured through scenarios only; v) models results remain by nature uncertain even though the modelers try to characterize this uncertainty and delineate it through scenario envelops and model comparisons. Sources of uncertainty in particular include: uncertainty in the system drivers (e.g. climate, population), uncertainty in the model parameters, and uncertainty in model structure, in particular in the way the food system is represented. For this reason, there is great value in working with ensembles of independent models.

Last but not least, it is important to highlight that models' value also depends critically on the quality of underlying data and behavior representations. With the COVID-19 crisis, the adequacy of the statistics currently used, and the relevance of the behaviors being assumed so far based on long-term historical observations are to be questioned, as new trends could emerge. Therefore, critical thinking and monitoring of recent developments are even more important to confront to model results for the years to come, to ensure that any new status in food systems conditions, and new paradigm can be adequately reflected in the models' behavior.

2. MODELING SDG2: THE INHERENT CHALLENGES TO SUFFICIENT, NUTRITIOUS, SUSTAINING, AND SUSTAINABLE FOOD

SDG2 covers a broad objective encompassing food security and sustainable production described as: "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" (UN, 2015). This goal covers five outcome targets (Figure 1). This objective contains its own intrinsic set of tensions and challenges.

The first two targets relate directly to the concept of food security and nutrition (FSN) developed around the recognition of human rights to adequate food (UN, 1996), and structured around the four following pillars: i) availability, ii) access, iii) utilization, and iv) stability (FAO, 1996).[2] These dimensions are key to understanding how to achieve SDG2, in particular Target 2.1 and 2.2 on adequate food supply and malnutrition. The food security pillars highlight the importance of producing enough food ("availability") but also the role of income and food prices ("access" pillar), which raises the questions of the cost of nutritious and healthy food, independently from the diversification of food sources ("utilization" pillar), which also touches to malnutrition. Targets 2.3, 2.4 and 2.5 extend the scope of SDG2 to the modalities of agricultural production. Target 2.3 puts a strong emphasis on farm income for small-scale farmers, linking to SDG1 ("No poverty"), through an increase of their farm productivity. However, this target should be reached without jeopardizing Target 2.4 that emphasizes sustainable production practices, and Target 2.5 that highlights the importance of keeping genetic diversity.

2 The High-Level Panel on Food Security also proposed to extend the food security concept with two additional pillars: v) agency and vi) sustainability, which would follow the broader approach taken by SDG2 (HLPE, 2020).

The different SDG2 targets therefore represent a consistent pathway to sustainable food systems but also can contain their own points of tension: how can we produce more, in a manner that is more healthy, more sustainable and more equitable -- all at the same time? This question garnered significant attention in the literature and needs to be first examined as it conditions many of the subsequent relations to other goals.

2.1. Providing adequate food for all and reducing hunger (Target 2.1)

The capability of humanity to produce enough food for its own subsistence has long been a source of concern. Malthus (1798) questioned the feasibility of a continuous population increase, and the Club of Rome report emphasized the limits to a continuous economic growth within a finite world (Meadows et al., 1972). The current UN projections predict 9.7 billion people globally in 2050 (+25% compared to 2020) with nearly a doubling of population in Africa (UN, 2019). And food demand will be further boosted by other drivers: income changes, dietary transition, urbanization, globalization, etc. (Kearney, 2010). FAO estimates that the total food calorie demand will increase by 39% between 2015 and 2050 (Alexandratos and Bruinsma, 2012; FAO, 2018),[3] and agricultural output will grow somewhat faster (40-45%), due to the need to produce feedstuffs for growing livestock consumption (Keyzer et al., 2005). Several authors anticipate even higher demand by mid-century with alternative assumptions on animal product demand: compared to FAO projected levels, Tilman et al. (2011) anticipate an increase of crop needs 50% higher by 2050, and Bijl et al. (2017) a 30% higher increase in food demand. Valin et al. (2014) compared estimates across global model projections and found a range of +43%–70% in food demand increase from 2015 to 2050, slightly above FAO estimates. And even when models reviewed disagree on the future level, most found much higher animal product consumption increase by 2050, with a range of 45%–160% spanning well above FAO's projected increase (55%). This anticipation is also supported by more empirical estimations (Gouel and Guimbard (2018) with 64–95%, Bodirsky et al. (2015) with 81%–102%, Bodirsky et al. (2020) with 76%). [4]

Under these conditions, the capacity of the global food system to sustainably supply all of the food required has been questioned. To understand the possible food security implications, food availability is usually estimated using the average dietary energy supply of the food system, in kilocalories per capita per day, but also using more sophisticatedly metrics such as the prevalence of undernourishment (Goal indicator 2.1.1). FAO estimates that 688 million people (8.9%) were undernourished in 2019, a trend increasing following the COVID-19 crisis (FAO et al., 2020). To calculate such prevalence, the food distribution supply profile per capita, in dietary energy terms, is compared to the average minimum dietary energy requirement in the population (Cafiero et al., 2014). This framework effectively captures the availability pillar of food security (more domestic supply reduces undernourishment) and can also be used in modeling to examine the response to average price or income changes (access pillar). Alternative metrics have also been proposed to measure undernourishment, such as the prevalence of underweight, based on up-scaled medical surveys (Bodirsky et al., 2020), or the number of children malnourished.[5]

Undernourishment metrics were implemented in various global economic models (Baldos and Hertel, 2015; Bodirsky et al., 2020; Hasegawa et al., 2015; Hasegawa et al., 2019), where it is also possible to capture the role of prices and income, as these determine the final level of food demand (Valin et al., 2014). Past modeling studies have often predicted a progressive decrease in undernourishment by 2050 following this indicator, under the effect of increased incomes and reduced inequality (which decreases the food distribution spread): down to 318 million (3.5%) undernourished in Alexandratos and Bruinsma (2012), 528 million (5.7%) underweight[6] in Bodirsky et al. (2020), less than 100 million (1%) undernourished for a middle-

3 For the projection from FAO (2018), the results from the BAU scenario for 2012-2050 were rescaled to the period 2015-2050 for comparability, assuming a constant growth rate.

4 The 2005-2050 estimates from Valin et al. (2014), 2010-2050 results from Gouel and Guimbard (2018) and 1990-2050 estimates were all rescaled to 2015-2050 for comparability, assuming a constant growth rate.

5 This indicator was also traditionally used in the IMPACT model (Rosegrant et al., 2017) using correlations between dietary energy supply and malnourishment statistics (Smith and Haddad, 2000). Even though more determinants of malnourishment could possibly be considered with the relation defining this metric, the indicator would primarily be determined by the average food availability, sole endogenous variable in the model entering the calculation, which gives it the same characteristics as the prevalence of undernourishment indicator.

6 Underweight and undernourishment values are relatively comparable. The global estimate of underweight people is 744 million in 2010 (Bodirsky et al., 2020), against 668 million for undernourished (FAO, 2020). However, regional and temporal patterns diverge, being lower for underweight prevalence in Sub-Saharan Africa and higher for Asia and showing a later decline than for undernourishment.

of-the-road scenario (SSP2) in Hasegawa et al. (2015). Overall, these results are very sensitive to the projections in inequality. For instance, the most unequal scenario (SSP3) in Hasegawa et al. (2015) results in a comparable level for undernourishment compared to today's situation.

The prevalence of undernourishment (PoU) indicator has been the workhorse of the modeling community recently to approach the question of hunger. However, this metric completely ignores the composition of the diets and the role of protein and micro-nutrients intake for a healthy diet (Springmann et al., 2016b). It also overlooks the multi-dimensionality of food security. Some first steps towards broadening the food security framework have been made recently (van Meijl et al., 2020a). In addition, it has been implemented across frameworks without harmonization of inequality projections within countries, which explains the large range of undernourishment projections (only average incomes per capita are harmonized for the SSPs quantified elements, for instance). Last, but not least, that indicator ignores the role of heterogeneity in income and price effects, and in particular the contrasted dynamics between rural and urban households (Hertel et al., 2010; Laborde Debucquet and Martin, 2018). More detailed analyses are therefore needed to better inform efforts aimed at tackling the challenge of Target 2.1 and 2.2 of SDG2, better integrating especially poverty modeling (see Section 3.1).

2.2. Dietary needs, nutrition transition and the triple burden of malnutrition (Target 2.2)

What we eat is as important as how much we eat when it comes to maintaining food security. This is why the "utilization" pillar is a key for food security. The example of animal production illustrates well various aspects of the challenges accompanying economic development. The nutrition transition influences our demand for nutrients like proteins and fat, and this also applies to other products (Bijl et al., 2017; Bodirsky et al., 2020; Gouel and Guimbard, 2018). At the same time, producing more livestock products is resource-intensive and comes with large sustainability impacts (Herrero et al., 2013; Steinfeld et al., 2006; Wirsenius et al., 2010). Consumption of seafood also provide high value nutrients (Béné et al., 2015; Hicks et al., 2019) but brings additional environmental challenges as one-third of marine catches are unsustainable (FAO, 2020b) and fast expansion of aquaculture adds to resource pressure and generates local pollution (Ahmed et al., 2018). Some other food products have very specific footprints due to their yield and production location, and trade mediated impacts can occur (Henders et al., 2015; Kastner et al., 2012). The choice of the diet can therefore have large implications for health and environment (Tilman and Clark, 2014). We explain below the different nutritional challenges associated to dietary patterns and discuss further in Section 3.2 the consequences for health as part of the synergies with SDG3.

To disentangle the complexity between nutrition needs and its impact, modeling diet composition is fundamental. Macronutrients are not the only important elements to represent, micro-nutrients are also essential to health (Burchi et al., 2011). Only a few modeling studies have examined the prospects on both macro and micronutrient provision at global level. Nelson et al. (2018) analyzed such scenarios at the horizon 2050 and found that dietary energy requirements would certainly be met in all regions, as well as protein intake needs, to the exception of a few least advanced countries. However, they anticipate insufficient supply of fat in low-income countries, and severe and persistent deficiencies in calcium, iron and folate, as well as several key vitamins (A, E, B12) in many parts of the developing world. These malnutrition impacts would be worsened under the effect of climate change, in particular as micronutrient concentrations in crops are expected to decrease under future elevated CO_2 concentration in the atmosphere (Beach et al., 2019; Myers et al., 2014).

Beside undernourishment and micronutrient deficiencies, a third important nutritional challenge is overweight and obesity, leading to the notion of the "triple burden of malnutrition" (Gomez et al., 2013). In 2016, the global "obesity pandemic" (Swinburn et al., 2011) was affecting 13.1% of adults around the world (FAO et al., 2020), and costing 3.3% of GDP in advanced economies (OECD, 2019). Projecting obesity in the context of food demand studies is rather recent. Based on detailed body mass distribution data, Bodirsky et al. (2020) calculated that about 45% of the population would be overweight by 2050, compared to 29% in 2010, based on the continuation of current food consumption patterns, and 1.5 billion people would become obese by mid-century (16%). Overconsumption of food associated to overweight brings large inefficiencies in the food system. Hasegawa et al. (2019) estimated that halting overconsumption by 2030 would reduce total caloric requirement by 6% and protein requirement by 9% globally. Therefore, even if these reductions would not suffice to address future food needs, there is a paradox of food distribution, with food deprivation for the poorest and overconsumption of food for another part of the population, illustrating the possible win-wins within the SDG Target 2.2 on malnutrition.

2.3. Producing more but growing more sustainably (Target 2.4)

Satisfying adequate dietary needs and eliminating malnutrition will require more food production as highlighted above, which may pose important risks for environmental sustainability of the food systems. The impacts of agricultural production increases on natural resources are well known (Springmann et al., 2018a; Tilman et al., 2001) and researchers have warned about the risks of exceeding a number of planetary limits (Rockstrom et al., 2009) due to agriculture intensification and expansion. Therefore, Targets 2.1 and 2.2 oriented towards provision of more adequate food and nutrition may be in tension with Target 2.4 that emphasizes the need of sustainable food production systems, improved agricultural practices, and ecosystems protection.

One of the most salient elements of the tension between adequate food supply and protection of the environment relates to land use. On the one hand, land needs mirror the concern that our current planet capacity may not suffice to feed its future population, and on the other hand, land use change has important implications for a number of SDG sustainability dimensions: carbon stocks for SDG13, biodiversity for SDG15, and the occurrence of zoonotic epidemics affecting SDG3. Many models have investigated the interplay of macroeconomic drivers, diet changes and future yield to determine the future land use requirements by the mid-century and beyond (FAO, 2018; Hertel et al., 2016; Popp et al., 2017; Schmitz et al., 2014; Smith et al., 2010; Stehfest et al., 2019). These studies usually find that agricultural land will continue its expansion with a range of ~5–20% for cropland and ~-10–+25% for pasture land (based on Smith et al. (2010) and Stehfest et al. (2019)). Figure 2 shows, through a simplified scenario decomposition, how different drivers of food demand – population, income per capita, diet preferences, overconsumption and waste - may influence the future demand by 2050, and how this future demand would result into a net land use change, after adjusting for projected technical change and climate change impact.

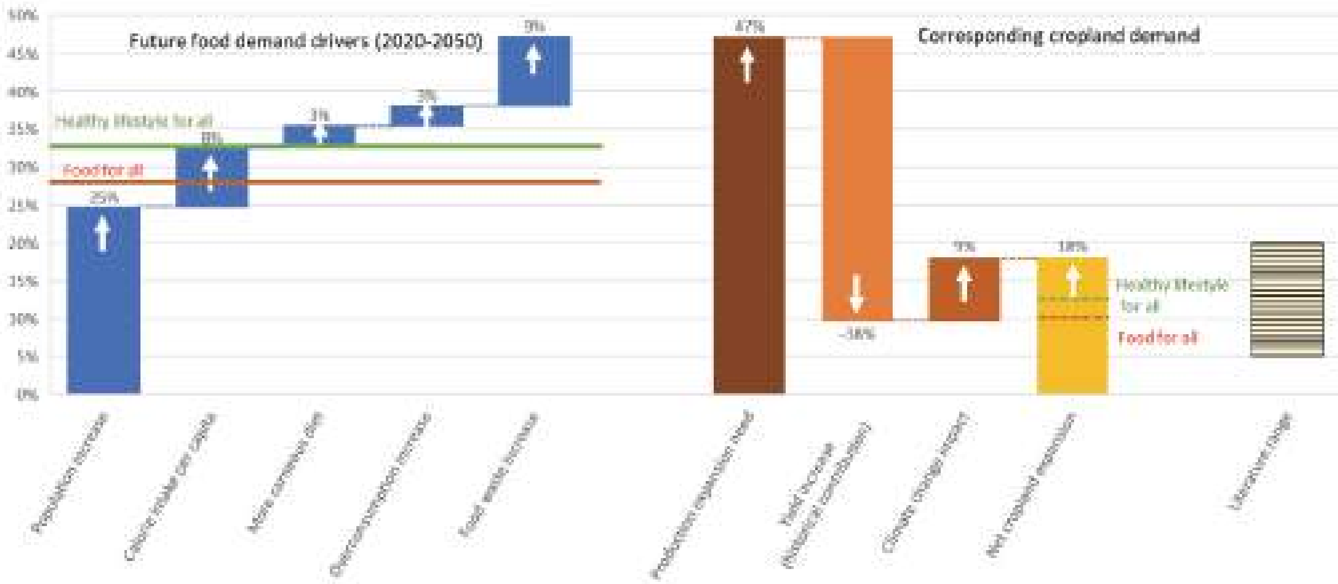
Virtually all studies predict further encroachment of cropland expansion into natural ecosystems (forests, biodiverse savannahs, wetlands) and the possibilities to avoid such damages remains disputed. The special report on land from the IPCC (IPCC, 2019) identified that out of 13 Gha of surface land, 9.3 Gha were already used, and only a quarter of the unused part (940 Mha) was unforested land (outside of barren, rocks etc.). Based on agroclimatic suitability consideration, FAO estimates that 400 million ha of non-protected areas would be suitable for rainfed cultivation expansion, mostly in low- and middle-income countries, in particular Africa and South America (FAO, 2018). This estimate would be reduced to about 260 Mha when considering 6h of distance to market as an extra criterion (Deininger and Byrlee, 2010). Some other literature assumes much higher availability, with less constraining criteria on land status or suitability (Eitelberg et al., 2014). Nonetheless, when these estimates are subject to closer scrutiny, they are significantly reduced. For instance, Fritz et al. (2013) reduces availability estimates from remote sensing data by 300–400 Mha when using field level information. Looking at various social and ecological trade-offs, Lambin et al. (2013) also reviewed data from global scale assessment in specific locations and found that effective availability would be less than a third of the theoretical top-down estimates. On the other hand, land suitability is not a static concept under climate change, and new regions could become cultivable as temperature and precipitation patterns evolve in the coming century, particularly in the Northern hemisphere (Sloat et al., 2020; Zabel et al., 2014).

The question of the pressure of agricultural production on natural resources extends much beyond land use expansion but also relate to land quality and many other elements (water, climate, nutrient balance, etc.). We present these in more details in Section 4 examining the impacts from SDG2 on other environmental SDGs.

2.4. The crucial role of agriculture productivity (Target 2.3 & 2.5)

Most common arguments against a Malthusian vision of the future rely on the idea that technical change could keep pace with future food demand growth and limit impacts on natural resources (Borlaug, 2002). Past productivity increases in agriculture have been substantial, moving from an input and machinery-based period of global productivity improvements during the Green revolution, to a knowledge-based one over the past three decades (Fuglie, 2010). There is still scope for further development of productivity as numerous innovations and new technologies emerge (Herrero et al., 2020; Ludena et al., 2007). And productivity gains will be crucial for future food security through their capacity to support income and offer lower food prices (Hertel et al., 2016), provided it also benefits to small producer net food seller (see also Section 5.2 on the role of trade). SDG target 2.3 highlighting productivity and income for smallholders therefore appears fully aligned with the food security objectives of SDG2.

Figure 2 Decomposition of future food demand from 2020 to 2050 (left-hand side, blue bars) and potential implications for cropland expansion based on stylized assumptions (right-hand side, warm colors). Total food demand increase (sum of blue bars – 47%) is the cumulated effect from population increase, calorie consumption per capita increase driven by economic growth, diet preference changes leading to more meat consumption and feed needs, overconsumption, and waste increase. The final demand increase (brown bar) is partly offset by the increase in yields (here based on an average 80% contribution share to match historical observations, orange), and future expected impact of climate change (dark orange). The net cropland expansion (yellow) can be compared to the literature range (striped bar). Food for all line in blue (yellow) bar corresponds to the level of increase in food (land) corresponding for sufficient caloric nutrition for all. Healthy lifestyle line corresponds to the increased level where all consumers with inactive lifestyle adopt a moderately active lifestyle. Sources: population increase: UN DESA; consumption per capita and livestock consumption impact Stehfest et al. (2019), based on GLOBIOM model; Overconsumption and waste impacts: Bodirsky et al. (2020); Historical yield contribution consistent with Smith et al. (2010), Burney et al. (2010), Fuglie et al. (2019); Climate change impact: RCP8.5 data from Leclère et al., 2014. Literature range: Stehfest et al. (2019) and Smith et al. (2010).



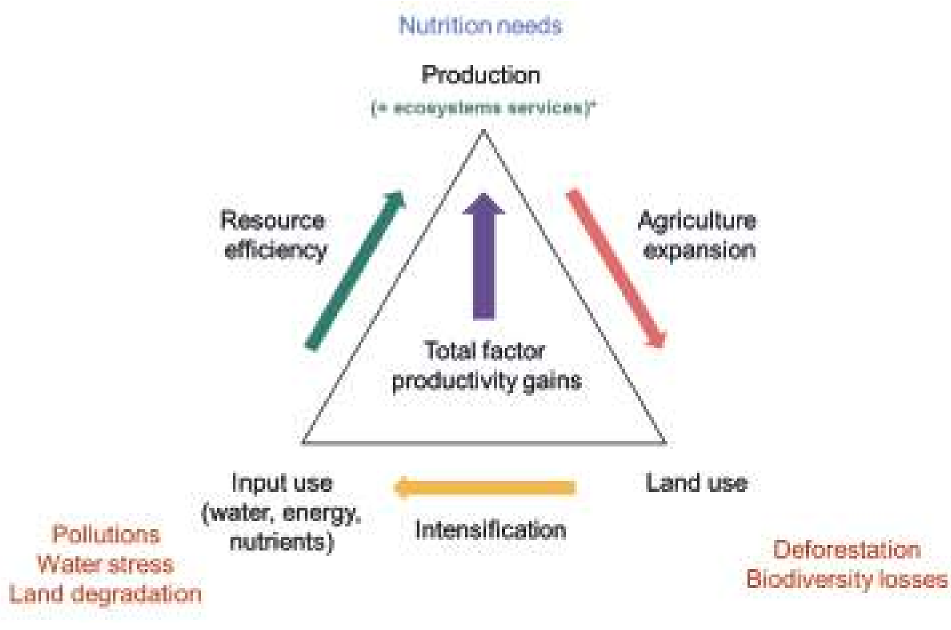
Among the different sources of agricultural productivity increase, land productivity has been particularly scrutinized, and is usually perceived as a key factor of economic development that allows mitigating the impacts emphasized above. Modeling studies have highlighted the direct role of yield on future trajectories of land use requirements (Balmford et al., 2005; Hertel et al., 2016; Stehfest et al., 2019). The prospects on future yield increase remains positive. On the one hand, technical margins exist to increase attainable yields through improved technologies and crop breeding (Fischer et al., 2009) and agricultural investments should support further progress (Baldos et al., 2018). On the other hand, the assessment of yield gaps indicate that large potentials exist to increase actual yields to the level achieved under best practices, but remain subject to local climatic and management constraints (Licker et al., 2010; van Ittersum et al., 2013). Mueller et al. (2012) identify that closing yield gaps globally could increase global crop production by 45%–70%, by optimizing water and nutrient management, and Folberth et al. (2020) estimate that reallocating crops accordingly could reduce cropland area by 50%. Simulation models have used such assessments to better anticipate future possible scenarios of yield development (van Zeist et al., 2020). Yield projections scenarios have clearly highlighted the substantial land sparing effects, but also pointed to the nitrogen consumption trade-offs (Tilman et al., 2011), and the greenhouse gas (GHG) emission reductions (Burney et al., 2010) as well as food security co-benefits (Valin et al., 2013).

However, from an economic standpoint, increasing productivity can lead to an ambivalent effect. On the one hand, the lower demand for resources per unit of output can lead to some environmental benefits. On the other hand, lower prices obtained through total factor productivity gains can lead to a rebound of consumption and increased exports, thereby partially or fully offsetting these benefits, an effect called the Jevons paradox (Alcott, 2005; Hertel, 2012b). This effect has been particularly identified in the case of cropland intensification (Byerlee et al., 2014; Ewers et al., 2009; Phalan et al., 2016; Villoria et al., 2013), but also irrigation water efficiency (Grafton et al., 2018). Modeling studies have illustrated how strategies oriented towards increasing yields could lead to mixed effect as food security (through increased production) and environmental outcomes would come in direct trade-off (Hertel et al., 2014; Valin et al., 2013). The potential for Jevons paradox calls for more attention to the ambiguous role that productivity gains (Target 2.3) could have on the environment (Target 2.4), as well as the need for protecting environmentally sensitive lands in the context of high rates of technological progress.

The other challenge associated with productivity increases is to ensure that, while saving on land resources, it does not bring any other environmental degradation. This is a particular concern for land intensification, as damages from high-input agriculture on ecosystems services have been well documented (Matson, 1997), most notably for biodiversity (Donald et al., 2001). A lot of attention has been devoted to identifying routes for sustainable intensification in the domain of nutrient and water management, pest control, soil protection to find win-win solutions (Foley et al., 2011; Tilman et al., 2002) – see also Section 4 on the relation between nutrient management, soil quality and food security. In the case of livestock, mixed intensive systems could leverage substantial environmental benefits both in terms of nutrient cycling, GHG emissions and land sparing, compared to extensive ones (Havlík et al., 2014). This is also the case for the fish sector where substantial productivity gains can be achieved in aquaculture (Waite et al., 2014). Therefore, improvements in agricultural productivity, in particular total factor productivity (related to all production factors), offers an opportunity to simultaneously lower the pressure on the environment and increase farmer income by decreasing the input requirements (Figure 3). To guide this change, Seppelt et al. (2020) illustrate how an optimum intensification level can be reached across production and environmental objectives by using a measure of green total factor productivity – or total resource productivity. Taking the case of biodiversity, they explain how such an approach could support sustainable intensification in low- and middle-income countries, and ecosystems value recovery in highly intensified regions. However, simulations towards 2050 suggest that more sustainable yield both for crops and livestock may also require drastic adjustments in our consumption patterns to avoid further deforestation (Erb et al., 2016).

Finally, increasing agricultural productivity is also key in the context of ongoing climate change impacts which are expected to grow over the coming decades

Figure 3 The role of total factor productivity (TFP) gains to limit impact of agricultural production on the environment (in red).



* Ecosystems services only for green TFP: indeed, some ecosystems services may be negatively affected while focusing on standard TFP gains (e.g. biodiversity). Accounting for ecosystems services value defines a green TFP that can guarantee a sustainable use of agricultural productivity gains (Seppelt et al., 2020).

and substantially affect crop yields (Rosenzweig et al., 2014), irrigation capacity (Schewe et al., 2013), labor productivity (de Lima et al., 2021), micronutrient availability (Beach et al., 2019) and ultimately food security (Hasegawa et al., 2016; Hertel et al., 2010; Janssens et al., 2020; Lloyd et al., 2018; Springmann et al., 2016b; Wheeler and von Braun, 2013). This paper does not delve further into the interplay of climate change impact and food security, as it has been extensively reviewed (Mbow et al., 2019). The importance of adaptation measures through yield responses has been largely emphasized and identified as a key factor to limit food security impacts (Leclère et al., 2014; Nelson et al., 2014; Weindl et al., 2015). Agricultural practices should also encourage resilience, to resist to occurrence of extreme events. Crop genetic diversity (Target 2.5) is representative of the measures fostering adaptation to climate change and resilience, also in the context of possible occurrences of new diseases and pest outbreaks.

3. SYNERGIES BETWEEN SDG2 AND OTHER SUSTAINABILITY DIMENSIONS

The "Zero Hunger" goal – and its different targets – is very closely connected to some other goals with which it operates in synergy, and, for some, even in full symbiosis. One of these is poverty elimination (SDG1), crucial for food access, and another is good health and well-being (SDG3), and the need for clean drinking water (SDG6). However, beyond these, a broader set of socioeconomic SDGs supports the progress of SDG2 and has been identified as key enablers (SDG4, 5, 8, 10, 11, 16, 17). We illustrate below how these have been approached by the modeling literature.

3.1. Food access and poverty (SDG1)

As analyzed in Section 2.1, food security not only relies on food availability but also food access. For that reason, considering the situation of households and individuals is important to correctly represent food security conditions, but is typical of large-scale modeling (Müller et al., 2020; van Wijk, 2014). For instance, aggregated approaches to PoU described above remain on the stylized representation of food distribution from FAO (Cafiero et al., 2014). Compared to the optimistic trends on hunger presented in Section 2.2, Laborde Debucquet and Martin (2018) look for instance at the implications of economic growth slow down for poverty in 29 developing countries with a sample of 300,000 households. They predict that in half of the countries, the extreme poverty rate will remain above 5% by 2030, with important consequences for food security. At a larger scale, Hallegatte and Rozenberg (2017) simulate the impact for 1.4 million representative households of a shift in agricultural prices and farm income due to climate change and find that the higher price effect would be predominant and increase poverty, which in turn would increase stunting (Lloyd et al., 2018). Other studies based on household modeling have illustrated the adverse impacts of food price increases on poverty (Hertel et al., 2010; Ivanic et al., 2012). However, higher prices could also in some situations increase farmer revenues and bring food security benefits (Hertel, 2015). Many scholars highlighted that, if in the short term, food price increases could be seen as detrimental for the poor, sustained food prices could be the best way to reduce rural poverty and improve food security for smallholders in the long term (Headey and Martin, 2016; Ivanic and Martin, 2014; Swinnen and Squicciarini, 2012). Therefore, if food security and poverty can be seen as part of a same battle, reduction of poverty should not only be sought through lower food prices but also through higher income, as highlighted by Target 2.3. In addition to the question of income, it is worth noting that SDG1 also insists on the role of access by poor households to land, natural resources and technologies (Target 1.4) and reduce exposure to climate events and relative risks (Target 1.5), two objectives that also strongly resonate with the Target 2.3 associating smallholder productivity gains and income increase.

3.2. Health and sustainability co-benefits from dietary changes (SDG3)

The relation between SDG2 and SDG3 on good health and well-being is also strongly synergistic, as nutrition is a key element of good health. First of all, malnutrition and health issues are strongly related in least developed countries, facing severe nutrition challenges. Maternal undernourishment and nutrient-deficiencies lead to fetal and child nutrition and development problems, reinforced through nutrient-inadequacies in breastfeeding (Black et al., 2013). The resulting stunting and wasting can increase mortality risks when children are exposed to infectious diseases. Conversely, many infectious diseases, such as measles, diarrhea, pneumonia, meningitis or malaria, can lead to increased risk of wasting and stunting risks for young children (ibid).

Furthermore, in all regions, adequate diet not only limits the risk of malnutrition but also prevents the prevalence of a number of non-communicable diseases, such as cardio-vascular diseases, diabetes, or cancer: in 2017, 17 million deaths and 255 million disability-adjusted life years would be attributable to dietary risks such as high sodium consumption, low intake of whole grain or low intake of fruits (Afshin et al., 2019). GHG emission-intensive products such as red meat are also contributing risk factors, which have led scholars to emphasize the co-benefits between health and sustainable agriculture. Tilman and Clark (2014) compare the impact of a conventional omnivorous diet with a pescatarian diet, a Mediterranean diet and a vegetarian diet, and find that moving away from current diets would be a win-win solution, with strong health benefits for the three alternative diets (5-40% relative risk decrease in cancer, diabetes and coronary mortality), and strongest outcome on environmental side with a vegetarian diet (more than 2 GtCO2e per year and 740 Mha of cropland saved by 2050). Springmann et al. (2016a) extend this type of analysis by looking at the implication of shifting to more plant-based diets by 2050 and find a decrease in global mortality of 6–10% and an abatement of emissions of 29–70%, leading to economic benefits of 1–31 trillion USD. More recently, the EAT-Lancet Commission proposed a more detailed sustainable and healthy diet prescription integrating a large number of dietary risks, with ambitious nutritional and planetary synergies (Willett et al., 2019). They find that adopting such a diet would allow reduce mortality by 19–23.6% by 2050. However, they also point out that providing such diet to all would require bridging the yield gaps by 75%, requiring substantial resource management improvements to be sustainably attainable. One other important limitation to the adoption of these healthy diets is the question of affordability. Hirvonen et al. (2019) estimated that the EAT-Lancet diet would cost at minimum 2.84 USD per day at 2011 prices and would be therefore inaccessible to 1.58 billion poor, due primarily to the share of fruits and vegetables required, and secondly to animal products. The diet was also found to be 60% more expensive, on average, than a least cost diet aimed at providing nutrition adequacy for 20 nutrients. In a follow-up analysis, the FAO et al. (2020) determined that healthy diets would be five times more expensive than a minimum energy diet, illustrating the extent of the income boost for impoverished households which would be necessary to make this diet accessible to all. Therefore, improving access to healthy diets cannot be dissociated from the progress on poverty elimination (SDG1).

One additional synergy between SDG2 and SDG3, comes from environmental health through a more sustainable agriculture (Target 2.4). Agricultural activities indeed substantially contribute to global pollution through various channels. First, through air pollution as biomass burnings from field management and land clearing contribute to fuel combustion emissions, responsible for 85% of all of the air pollution burden, itself the largest source of pollution-related diseases (Landrigan et al., 2018). Agriculture ammonia emissions also impact human health by contributing to formation of fine particle matters in the air (Stokstad, 2014), and generating several hundred thousand premature deaths per year globally (Giannadaki et al., 2018). A second channel of impact occurs through water pollution: excessive fertilizer application and manure management lead to pollution in the watersheds (Section 4.3) to which add more complex compounds coming from pesticide and herbicide applications (Evans et al., 2019; Schwarzenbach et al., 2010). A third channel of impact comes directly through the food and beverage we eat, with traces of pesticide leading to closely monitored ingestion levels (Nougadère et al., 2012). Chronic exposure to pesticide – directly for farmers or indirectly through air, water and food – has be found to increase risk diseases (Alavanja et al., 2004; Landrigan et al., 2018). Such impacts on health are not yet modeled at large scale due to the methodological uncertainties but reduction of pesticide use has been highlighted as a key component of sustainable agriculture (Möhring et al., 2020; Nicolopoulou-Stamati et al., 2016).

A last area of synergy between SDG2 and SDG3 attracted more attention since the COVID-19 crisis: the risk of zoonosis epidemic associated to expansion of human settlements and agriculture into wilderness areas (Morse et al., 2012), directly referred to in Target 3.3. Even though no foresight study is available to date to predict the link between future scenario for agriculture and risk of emergence of new diseases, the role of land use change in the zoonosis risk is now well recognized (Gibb et al., 2020; Patz et al., 2004). Furthermore, intensive livestock farming is also well known for increasing risks of zoonosis emergence (Jones et al., 2013) leading to considering the concept of "One health" as a key component of the food systems sustainability (Coker et al., 2011).

3.3. Education, gender equality, decent work and other socioeconomic enablers (SDG4, 5, 8, 10, 11, 16, 17)

A comprehensive view of food systems encompasses a large set of socioeconomic drivers and outcomes (Ericksen, 2008; HLPE, 2017; Ingram, 2011). Therefore, many other SDGs are also connected to SDG2 and support its achievement. These have been identified in Figure 1 as a single block of socioeconomic enablers but obviously interact in a more complex manner with SDG2. These are education (SDG4), gender equality (SDG5), decent work and economic growth (SDG8), reduction of inequality (SDG10), sustainable cities and communities (SDG11), peace, justice and strong institutions (SDG16), and partnership for the goals (SDG17). These are usually not well represented in global quantitative studies, therefore will be only briefly covered here. However, some of these enablers can play important roles for food security and other SDG2 dimensions. Therefore, better assessing the associated synergies around these goals for food systems should be an important objective for future quantitative assessments.

Among these goals, education (SDG4) is a first important development driver influencing consumption patterns and healthy diet choice (Hiza et al., 2013). Target 4.7 highlights education to sustainable lifestyle, which goes one step further into supporting sustainable food systems. And Target 4.b insists on the importance of training in science and engineering, which can support more sustainable management and research (Target 2.a). In developing regions, education is also an important pillar for the improvement of maternal and child nutrition (Alderman and Headey, 2017; Ruel and Alderman, 2013). As highlighted above, food security and poverty are also closely associated. Higher smallholder incomes (Target 2.3) should therefore help for schooling of children in rural areas by limiting contribution to family labor in agriculture.

Gender equality (SDG5) is another key goal for food security as female workers account for a substantial share of the agricultural workforce at 40-50% in developing countries (FAO, 2011), with even larger shares in some sectors and regions (e.g. 70% for upland rice in Indonesia). However, women face difficulties to access land, livestock, education, extension and financial services, and equal employment conditions to those of men (wage, stable contract, off-farm opportunities). According to FAO (2011), targeting these inequalities would allow reducing undernourishment by 100-150 million persons. At the same time, women play a key role for food security in the household, and their nutritional status also influences those of their young children (Black et al., 2013). SDG5 can therefore support income and productivity increases (Target 2.3) for small-scale women farmer by enhancing their access to land and natural resources (Target 5.a) (Agarwal, 2018) and empowering them to safeguard the nutritional status in the households.

Decent work and economic growth (SDG8) and reduction of inequality (SDG10) can also support better nutrition by going beyond SDG1 and bringing economic resources (Target 8.1 and 10.1) to households for accessing healthy food. Targets 8.2-8.4 also put emphasis on productivity, diversification, technological upgrading, formalized small-scale enterprises, and resource efficiency, all supportive of Targets 2.3-2.5. Nonetheless, economic growth can also steer unsustainable behavior for the food systems, such as overconsumption and waste (Section 5.4). Sustainable cities and communities (SDG11) put an important emphasis on urban and rural areas harmonious integration and planning, which would support Target 2.1 of greater access to sufficient and nutritious food in cities.

Peace, justice and strong institutions (SDG16) have a key role to play for food security as conflict remains one of the most severe drivers of severe undernourishment and food crises (FAO et al., 2017). Furthermore, farmers' rights, in particular land tenure, and solid institutions are key to secure the situations and income of small-scale farmers. Partnership for the goals (SDG17) emphasizes the role of Development Assistance, for rural economic development in developing countries, and the need to address the most serious food crises through humanitarian aid. It also encourages international knowledge transfers, which directly supports Target 2.a (see Section 5.1).

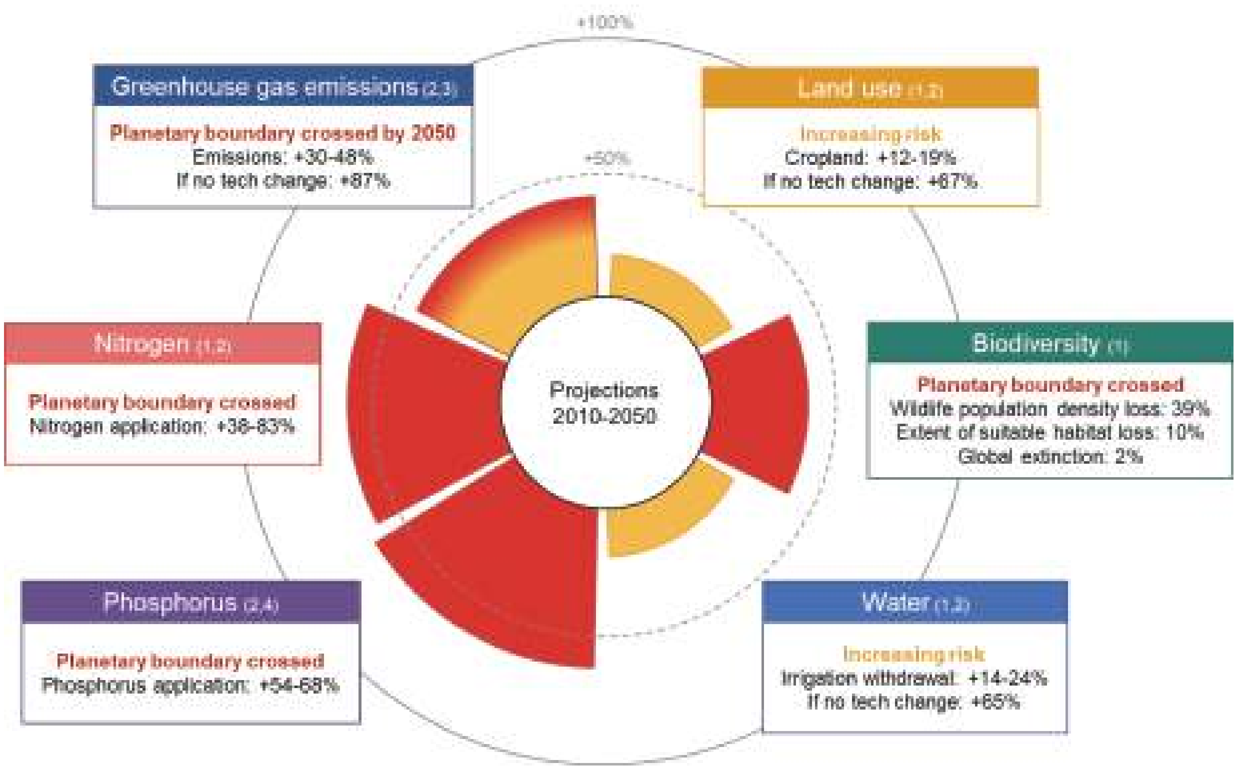
4. TRADE-OFFS BETWEEN SDG2 AND ENVIRONMENTAL GOALS

Feeding the world sustainably will unfortunately not be achievable without tensions. As illustrated in Section 2.3, growing more food for SDG2 will pose some serious challenges for natural resources, and the final impacts will depend on future food demand and our capacity to create a more resource-efficient and sustainable agriculture globally. One of the commonly adopted frameworks to represent global sustainability in the Anthropocene is the planetary boundaries approach, which defines thresholds on resources and ecosystems usage which must not be exceeded if we are to remain within a sustainable exploitation of our planet (Rockstrom et al., 2009; Steffen et al., 2015). In the analysis of the boundaries as proposed by Rockstrom et al. (2009), six are directly relevant to agriculture (climate change, biodiversity, nitrogen, phosphorus, freshwater use, land use change), and three of these boundaries have already been exceeded: nitrogen cycle, biodiversity loss and climate change. In an update to that framework, Steffen et al. (2015) additionally identified phosphorus and land use as having exceeded the Earth's safe operating space. Several papers have subsequently analyzed the extent to which agriculture contributes to these environmental challenges in the future. Using a global agricultural market model, Springmann et al. (2018a) projected that if current trends were to continue without any change of technical level, the number of boundaries crossed by 2050 would be up to five: in addition to GHG emissions, cropland use, nitrogen and phosphorus application, the extraction of blue water would be an additional limit exceeded. Gerten et al. (2020) analyzed that half of the current production system would already transgress some of these boundaries globally and respecting these environmental limits would only allow feeding 3.4 billion people globally. All of these authors propose mitigation measures and transformations that would allow overcoming these limitations while also achieving food security and environmental sustainability by 2050. These system transformations will be discussed in Section 6.

Figure 4 illustrates how the different planetary boundaries would be crossed by 2050 according to selected modeling studies. Here, displayed ranges of expansion for each variable are based on projections from economic and integrated assessment models taking into account technical change. Under that assumption, three boundaries are crossed already in 2010, and GHG emissions are crossed by 2050. Land use and water withdrawals are not marked as crossing boundaries by 2050 but only at “increasing risk”, to the difference of Springmann et al. (2018a), because technical change buffers a part of the future impact.

The challenges highlighted through the planetary boundary framework provide an overview of the larger set of trade-offs enshrined within the SDGs. In this section, we explain in more detail how these different challenges have been studied in modeling studies and what their mitigation options are. Furthermore, the success of the Agenda 2030 also depends on the achievement of other goals. We highlight here how some SDGs, associated to ambitious targets, may enter in competition with SDG2 and bring additional challenges for the food system.

Figure 3 Projections of the food systems pressure along selected environmental dimensions (Visual representation inspired from the planetary boundaries, Steffen et al., 2015). Colors of the sectors indicate the status for each planetary boundary: green = no risk (none); orange = at risk of crossing by 2050; red = boundary crossed (plain if crossed already in 2010, gradient if crossed by 2050). Sector size corresponds to the range of values covered by the sources (subscripts in the box titles). For source (2), no technical change is assumed for the projection, which may significantly increase the impact; these numbers are therefore only reported for information when out of the range of other studies, and not used to calculate the sector size. Greenhouse gas emissions only account for non-CO2 emissions from agriculture.
Sources used (box title subscripts): 1 – Leclère et al. (2020): GLOBIOM, IMAGE, AIM, MAgPIE models; 2 – Springmann et al. (2018), baseline (without technical change), IMPACT model; 3 – Frank et al. (2018), GLOBIOM, IMAGE, CAPRI, MAGNET models; 4 – Mogollon et al. (2018a), IMAGE model.



4.1. Contribution to climate change and trade-offs with nature-based solutions (SDG13)

One of the most widely studied adverse environmental impacts of the food system is its contribution to climate change. The food system (including agriculture, food supply chain and waste management) is considered to represent today 34% of total anthropogenic GHG emissions (Crippa et al., 2021) and direct emissions from agriculture are expected to keep growing over the coming decade, mostly through direct CH4 and N2O emissions (Popp et al., 2010), whereas land use change emissions would decline (Popp et al., 2017; Valin et al., 2013). The unabated increase in agricultural emissions could potentially compromise the feasibility of the Paris Agreement (Clark et al., 2020). For that reason, agriculture is expected to contribute to mitigation efforts (Wollenberg et al., 2016), but this reduction of emissions should be achieved without compromising food security (Smith et al., 2013). How can agricultural emissions be reduced? Internalizing the GHG emissions externality from agriculture would result in much higher production costs and food prices, thereby giving rise to diminished food availability and affordability. Based on a multi-model analysis, Hasegawa et al. (2018) found that applying the same carbon tax to agriculture as to other sectors for a +2°C climate stabilization scenario could put on average 70 million more people at risk of undernourishment. This number could rise to 160 million for a +1.5°C ambition (Fujimori et al., 2019). However, a differentiated policy of taxation focusing on the land use sector would limit these risks and keep food security impact at lower level (Golub et al., 2012; Havlík et al., 2014; Tabeau et al., 2017), thanks to the low costs of CO2 abatement in the land using sector (Golub et al., 2009; Kindermann et al., 2008). Non-CO2 emissions likely to be more costly to abate (Frank et al., 2018a; Frank et al., 2018b), in particular in the livestock sector (Havlík et al., 2014). However, some win-win technical solutions exist, in particular with yield improvements in crops (Valin et al., 2013) and feed conversion efficiency improvements and market adjustments for livestock (Havlík et al., 2014; Henderson et al., 2017). Improving soil organic carbon sequestration through conservation tillage would also be a promising option to reduce GHG emissions, improve yields and income, as well as food security (Frank et al., 2017; Lal, 2010). Budget neutral taxation schemes that recycle carbon tax revenues to support the poor and improve food security could even decrease global poverty rate and foster SDG1 and SDG2 simultaneously globally (Soergel et al., 2021).

Reducing emissions from the food systems is only one of the climate change mitigation channels. In addition, land may also be used as a resource to help decarbonize the economy by producing cleaner sources of energy and substituting fossil fuels, which raises a food-energy-environment trilemma (Tilman et al., 2009). Indeed, while a substantial part of the energy system can be electrified, some other sectors like aviation, shipping and to some extent heavy load transport will have difficulties to decarbonize with other forms of renewable fuels than biofuels (IRENA, 2020). In addition, limiting emissions will not be sufficient to stabilize the climate (IPCC, 2019), and negative carbon technologies will be necessary, for which increasing the land sink through afforestation, soil carbon sequestration and bioenergy with carbon capture are among the most scrutinized options (Field and Mach, 2017; Smith et al., 2015). Current biofuel policies have already raised significant concerns as to their feedback on food security (Ewing and Msangi, 2009; Persson, 2015; Searchinger et al., 2015). Large deployment of bioenergy for climate mitigation would imply much larger land demand (Creutzig et al., 2012; IPCC, 2018; Popp et al., 2017). In a multi-model comparison, Lotze-Campen et al. (2014) found that pressure of second-generation biofuels on the food market could remain limited to a 3–10% increase if land expansion were to occur mostly in new land, an impact lower than the one from climate change. Havlík et al. (2015) also reach a similar conclusion by comparing bioenergy deployment to other mitigation efforts in the agricultural sector. However, much larger scale deployment would not prevent competition with food. Hasegawa et al. (2020) find that for a level of deployment of 200-300 EJ of high yield bioenergy (500 Mha) necessary for negative emissions, cropland would reduce by 53 Mha on average and food prices increase by up to 40%, leaving 0-25 million people at risk of hunger. Similarly, Kreidenweis et al. (2016) find that afforesting the land surface by 0.9-1.6 Gha would trigger a food price increase of 50-90% by 2050. For that reason, the incentives for growing new forest and plantations will have to be used with care and more efforts of abatement will be needed in other sectors to limit reliance on negative emissions (Grubler et al., 2018; van Vuuren et al., 2018).

4.2. Water resource competition and environmental flow requirements (SDG6)

Overconsumption of water resources is another critical challenge faced by agriculture. Irrigation represents today 70% of global water withdrawals, and this demand is expected to continue to increase in the coming decades (FAO, 2020a; Lotze-Campen et al., 2008; Palazzo et al., 2019; Tilman et al., 2001). Due to their higher productivity, irrigated areas could serve as an option for improving food security in some contexts. However, this solution would not be suitable for all regions.

Palazzo et al. (2019) estimate that increasing irrigated areas by 32% in developing regions by 2050 would require an average annual investment cost of 26 billion USD and would not be sustainable for regions like Northern Africa and South Asia. Globally, ~30% of total water withdrawals are considered non-sustainable today, either because they compromise ecosystems' functioning or because they exceed the renewal capabilities of underground water reserves. This situation will likely worsen with the impact of climate change (Schewe et al., 2013), in particular with the development of new hotspots of water scarcity (Byers et al., 2018). Unsustainable withdrawals may reach ~40% by end of the century (Wada and Bierkens, 2014).

Reducing water consumption to a level respecting environmental flow requirements of water streams would require substantial reductions in irrigation, decreasing irrigated production's share of global output from 40% to 20% by 2050 and reducing irrigated areas (20% of current cultivated area) by nearly one-thrid (Pastor et al., 2019). However, imposing constraints on irrigation could put close to 1 million people at risk of hunger by 2050 and degrade other SDGs according to Liu et al. (2017). Therefore, improving water use efficiency appears crucial to boost water's footprint per crop calorie (Brauman et al., 2013), and animal protein (Heinke et al., 2020). However, water efficiency investments could also lead to rebound effects in line with the Jevons paradox and such investments would be mostly only be beneficial if accompanied with other resource conservation measures (Grafton et al., 2018). In addition to productivity gains, inter-basin water transfers and international trade are also cited as additional options to facilitate the sustainable use of irrigation (Liu et al., 2017). For instance, Pastor et al. (2019) find that an increase in international trade by 10-13% would compensate for a sustainability constraint on irrigation by 2050, or by 17-20% if the impact of climate change is also considered. As a consequence, safeguarding environmental flows in some regions could add some pressure on the competition for productive land and lead to further land expansion in other places (Bonsch et al., 2015). For these reasons, it appears clear that the best mitigation strategy for water will require adapted solutions based on the local context, with the right balance between water-efficient technologies, resource preservation, improved market access and adaptation capacity for more resilience.

To add to this challenge, water needs for domestic and industrial use, including clean electricity production from hydropower, are also expected to grow (Fitton et al., 2019; Strzepek and Boehlert, 2010). According to Wada and Bierkens (2014), both domestic and industrial uses of water could increase by about 65% from 2010 to 2050, which would mean their share of water extraction would increase from 30% globally to 40% under the assumption that irrigation area would not expand. This indicates growing tension around the use of scarce water resources. Consequently, a large literature has emerged to try to better represent the challenges at the food-water-energy nexus (Endo et al., 2015), illustrating the entanglement of various SDGs around the water resource, beyond the SDG2-SDG6 relation.

4.3. Nitrogen and phosphorus pollution (SDG6)

Nitrogen (N) and phosphorus (P) cycles represent two planetary boundaries estimated as critically exceeded (Steffen et al., 2015). The leaching and run-off of N and P surplus in agriculture trigger eutrophication of terrestrial and marine ecosystems, including the development of hypoxic conditions in coastal waters causing fish mortality. In addition, excess of N generates acidification of soils and freshwater; N2O climate-warming emissions; air pollution through ozone formation; groundwater contamination from nitrate; and stratospheric ozone depletion induced by N2O emissions (de Vries et al., 2013; Kanter et al., 2020; van Vuuren et al., 2011a). Nutrient cycle imbalances therefore threaten at least directly five SDGs (SDG3 on health, SDG6 on water, SDG13 on climate, SDG14 life in water, SDG15 on life on land). Nonetheless, the additional input of these nutrients is key to increase yields in food insecure regions (Mueller et al., 2012; van der Velde et al., 2013).

Nitrogen use has historically been rising faster globally than crop production (Lassaletta et al., 2014), and future global agricultural projections let anticipate large further increases in nitrogen application (Bodirsky et al., 2014; Eickhout et al., 2006; Mogollon et al., 2018b; Sinha et al., 2019). As a consequence, nitrogen pollution is expected to increase. Bodirsky et al. (2014) anticipate a +25% increase in nitrogen surplus between 2010 and 2050 for a business-as-usual scenario, whereas Mogollon et al. (2018b) come with a much larger estimate at +90% for their central case between 2005 and 2050. At the same time, increased nitrogen application in some regions can bring environmental co-benefits through land sparing. Tilman et al. (2011) find that focusing N increase in developing low-yielding regions would allow reducing emissions induced by agriculture by two-thirds and land expansion by 80% by 2050 compared to a similar N application increase in high yielded developed regions. Considering the high heterogeneity in performances, improving crop nitrogen use efficiency appears as an important source of mitigation potential for the fertilization pollution impacts (Zhang et al., 2015). Redistributing current fertilizer use more efficiently would allow increasing production by 30% (Mueller et al., 2014). However, to bring surpluses below critical thresholds in pollution hotspots, efficiency improvements are not always sufficient and stronger local solutions will be needed. Better livestock management, spatial relocation and lower animal production levels - requiring diet changes and food waste reduction - are among the measures usually simulated to reduce further N environmental impacts (Bodirsky et al., 2014; Bouwman et al., 2011; Gerten et al., 2020; Havlík et al., 2014).

The prospects of phosphorus present similar dilemma, with a substantial increase in demand for the coming century under current scenarios. Springmann et al. (2018a) anticipate an increase in P application in agriculture by 54% from 2010 to 2050, whereas Mogollon et al. (2018a) project an increase of 68% for the same period.[7] This latter work extends the previous estimates from van Vuuren et al. (2010) anticipating with the same model a 63-105% increase for three out of four scenarios of P consumption. However, accumulation and saturation of P in soils could also result in lower increases or a stabilization of fertilization needs by 2050 compared to current levels (Sattari et al., 2012). Van Vuuren et al. predict that P reserves would remain sufficient to satisfy the strong increase by the end of the century, in spite of the risk of resource exhaustion. However, the phosphorus cycle across regions reveals substantial disparities in surplus and deficit (MacDonald et al., 2011; Zhang et al., 2017), which may require resource rebalancing between regions through trade. In regions with surplus, environmental impacts on fresh water can be significant (Carpenter and Bennett, 2011). Phosphorus pollution mitigation would primarily require a reduction of soil erosion and the recycling of manure in landless livestock systems. Moreover, point sources to aquatic systems from wastewater, aquaculture and manure disposal have to be eliminated. A greater consideration to international imbalances due to traded P embedded in food products could also support a more efficient P global recycling (Lun et al., 2018).

4.4. Terrestrial biodiversity impacts and conservation needs (SDG15)

The global food system is among the main causes behind the sixth massive species extinction on Earth. Land use change and overexploitation of resources, closely associated with the food sector, are estimated to be the largest drivers of biodiversity losses, followed by climate change impacts and water pollution, both of which are also partly driven by the food system (IPBES, 2019; Maxwell et al., 2016). Expansion of agriculture into various other natural ecosystems significantly contribute to impacts on biodiversity through loss of ecosystems intactness, abundance and richness of species (Creutzig et al., 2019; Jung et al., 2019; Newbold et al., 2016). Newbold et al. (2015) find that past pressures from land use change have reduced globally on average within-sample species richness by 13.6% and abundance by 10.7% over the past centuries with much higher losses in hotspot regions (76.5% and 39.5% respectively). Using integrated assessment model-driven land use scenarios, they anticipate that this decline will continue with, on average, a further loss of -3.4% in species richness by the end of the century (+25% impact on top of historical losses), with much larger local consequences. This work confirms the results of several previous forward-looking analyses using simpler indicators of biodiversity (Sala, 2000; van Vuuren et al., 2015). New generations of integrated global land use scenarios with advanced ecosystems services modeling have been developed recently (Kim et al., 2018). Combining four global land use economic models and nine models of biodiversity, Leclère et al. (2020) found, under a business-as-usual scenario, a continuous degradation in a large range of biodiversity indicators over the period 2010-2050. Those indicators experiencing these losses included: wildlife population density, extent of suitable habitat, local compositional intactness, regional and global extinctions. Only drastic mitigation measures combining demand side measures (diets shift, waste reduction), supply side adjustments (yield increase, trade policies), and increased conservation (protected areas, land restoration payments) would enable mitigating these impacts. It is also possible to approach the role of the food system at a more granular level. Using an attribution approach based on patterns of land use, Chaudhary and Kastner (2016) determine that domestic food consumption was responsible for 83% of the biodiversity losses attributable to agriculture-driven land use change, versus 17% for traded food products. They also highlight the substantial role of crops such as sugar cane, palm oil, rubber and coffee in imported biodiversity losses. All of these studies emphasize the critical role played by agricultural development in hotspots of biodiversity in the tropics which is well in

7 Mogollon et al.'s (2018) results are rescaled from an initial 79% increase on the period 2005-2050.

line with the empirical literature (Busch and Ferretti-Gallon, 2017).

To mitigate the collapse of biodiversity, some ambitious measures of conservation and also large land restoration programs are proposed, as illustrated by the aspirational target of returning half of the Earth's surface back to nature as proposed by Wilson (2016). The food system impact from such ambitious restoration measures would be high. Using a static analysis, Mehrabi et al. (2018) find that saving Half-Earth would imply a decrease of cropland by 15-31%, pasture by 10-45%, and require a 3-29% and 23-25% decrease in food and non-food crop calories, respectively. Additionally, at least 1 billion people would need to be resettled (Schleicher et al., 2019). Forward-looking assessments have been used to explore more precisely the extent of land return to nature needed to restore biodiversity. Using a multi-model analysis, Leclère et al. (2020) found that biodiversity losses could be halted by 2050 by restoring 430 to 1,460 Mha of land. This would require substantially increasing the commitments taken in the context of the Bonn Challenge (350 Mha by 2030). However, they also show that if land conservation and restoration were implemented alone, food prices would increase by up to 20%. These authors conclude such measures need to be complemented with other changes on the production and demand side policies to allow reverting biodiversity losses without impact on food security.

In addition to these impacts on the agricultural extensive margin, intensive agricultural practices can also affect biodiversity, as already highlighted in Section 2.4. Avoiding these impacts while still fulfilling SDG2 requires adoption of sustainable intensification strategies (Cunningham et al., 2013; Deguines et al., 2014). As illustrated by the land sharing vs land sparing debate (Phalan et al., 2011), a balance needs to be found between the possible impacts from cropland on local biodiversity and the losses induced by agricultural land expansion. Some authors insist on the importance of the local context and the analysis of specific landscape scenarios to assess the best strategy for biodiversity between an intensification (sparing) or an extensification (sharing) approach (Law and Wilson, 2015).

4.5. Land degradation (SDG15)

Land degradation is an additional growing threat specially identified through Target 15.3 aiming for degradation neutrality. Among the various ecosystem services affected, agriculture is one of the most exposed (Nkonya et al., 2016). According to UNCCD (2017), 20% of cropland and 19% of grassland showed a persistent decline in productivity over the period 1998-2013, which directly impacts agricultural production in these areas. This dynamic can lead to rural poverty traps and food insecurity: Barbier and Hochard (2018) estimate that 1.3 billion people lived on degraded land in 2010 and this population rose by 11.1% between 2000 and 2010. Land degradation is partly driven by external factors (climate change, sea level rise, human occupation pressures), but agricultural practices also play a role in degrading the soil conditions (erosion, compaction, loss of structure and nutrients). In rural areas, soil degradation and food insecurity are intimately related, due to the importance of soil for crop fertility and nutrient provisioning (Lal, 2009). Increased aridity, affecting 40% of arable land, is a major factor in arable land degradation when coupled with unsustainable land management, followed by soil erosion with 20% (Pravalie et al., 2021), which depletes nutrient stocks, in particular phosphorus (see Section 1.1). This situation has been examined through forward-looking studies as well. Using model projections, van der Esch et al. (2017) analyze the future land degradation dynamics by 2050, and estimate for instance that 27 Gt of additional soil organic carbon would be lost globally, compared to 2010. Exposure to degraded land would also increase, with 40-50% more population living in drylands, a growth rate twice higher than in the rest of the world. They also find that by 2050 an additional 5% increase in land expansion globally would be attributable to the effect of reduced land productivity due to soil fertility loss and land management. Mitigation measures against arable land degradation are therefore crucial. In the case of soil management, these include in particular conservation agriculture, integrated nutrient management, continuous vegetative cover as well as more sustainable practices in the livestock sector, such as lower stocking rates to avoid overgrazing (Lal, 2015). Strong synergies can be found in these areas with climate change mitigation (Frank et al., 2017; Smith et al., 2019).

4.6. Fisheries and marine life conservation (SDG14)

Fish is an essential food source in many regions and is rich in micro-nutrients. However, overfishing is putting important pressure on marine fish population and reduces catches in low-income food deficit countries by around 15% (Srinivasan et al., 2010). Falling fish catches therefore pose serious risk of malnutrition for vulnerable populations and are essential to address (Golden et al., 2016). Protecting life in the oceans is also at the center of the SDGs (SDG14). There is a fear that marine conservation could conflict with food security along a similar trade-off dynamic as for land. Ocean wilderness area represent approximately 13% of the ocean area but only 4.9% of this area is protected (Jones et al., 2018a). Furthermore, the vast majority of the top 10% priority areas for biodiversity protection are located within the exclusive economic zones of coastal nations and therefore conflict with potential fishing activities (Sala et al., 2021). However, assessments converge on the fact that marine protected areas could bring win-win solutions to both biodiversity and fisheries by reconstituting fish stocks in overfished areas, and benefiting yields of adjacent fish zones (Cabral et al., 2020; Kerwath et al., 2013; Roberts et al., 2005). Sala et al. (2021) estimate that optimizing conservation strategies would allow increasing fish catches by 6 Mt annually, protect 28% of the ocean and secure 35% of biodiversity simultaneously. It would even be possible to protect up to 71% of the ocean and 91% of the biodiversity without any reduction in catches. This highlights the strong potential for win-win solutions between food security and ocean conservation with well-tailored strategies.

4.7. Competition for land with urbanization and infrastructure needs (SDG9 & 11)

The expansion of food systems will put pressure on land use, as highlighted in Section 2.3. However, these expansion needs will also face the development of cities and peri-urban areas. Even though SDG9 and SDG11 are aimed at supporting a sustainable integration of the urban and rural worlds, development of cities will increase the level of food demand due to higher consumption of transformed products, and also trigger expansion of infrastructure and land uptake for urban areas. According to Bren d'Amour et al. (2016), urban areas are expected to triple during the period 2000-2030, and could take between 1.8 and 2.4% of global cropland, mostly in Asia and Africa, and 3–4% of crop production due to the higher productivity of that land. This area lost to agriculture could be three times higher than those figures if peri-urban and village systems expansion were also considered (van Vliet et al., 2017). Due to urban encroachment into cropland, indirect effects of land displacements are to be expected (Barthel et al., 2019). van Vliet et al. (2017) project for instance 35 Mha of additional indirect cropland expansion by 2040. FAO (2018) assume in their most recent foresight a decrease of land suitable for crop cultivation of 1.6–3.3 Mha/yr in the coming decades, based on estimates from Lambin and Meyfroidt (2011). These pressures required by the growth of cities, peri-urban areas and overall infrastructure need to be considered in the nexus of future tensions around land.

5. TOWARDS SUSTAINABLE PATHWAYS: TRANSFORMING THE FOOD SYSTEM FOR THE AGENDA 2030

With all of the impacts and challenges highlighted above, there is a consensus that the global food system needs deep changes in the 21st century to support achievement of the Agenda 2030 (Food and Land Use Coalition, 2019; Schmidt-Traub et al., 2019; Smith et al., 2019). Large-scale transformations will be required, both on the supply and demand sides (Smith et al., 2013). In this section, we highlight the role of some key enablers, the first ones already integrated to SDG2 with the Targets 2.a, 2.b/2.c, but also other transformation options on the demand side. These specific enablers complement the more general ones already embedded in the socioeconomic SDGs covered in Section 3, in particular SDG1 on poverty elimination, and SDG 16 and 17 highlighting the role of governance and international partnership. We summarize the main findings from modeling studies combining these various transformation options into ambitious transformation scenarios leading to sustainable pathways.

5.1. Investment, research, and innovation for sustainable agriculture (Target 2.a)

We have seen that agricultural productivity gains are crucial to the attainment of SDG2 (Section 2.4) and for mitigation of adverse impacts on other SDGs. Significant investments and technology transfers will be required for this purpose, as highlighted by Target 2.a, in sectors such as market infrastructure, irrigation, and research and development (R&D) -- the latter being crucial for technical progress. Public spending on agricultural R&D has tripled in developing countries between 1981 and 2011 and now equals those of developed countries at more than $22 bn per year (in 2011 PPP$, Fuglie et al. (2019)). However, budgets remain very uneven depending on the region. In Sub-Saharan Africa, R&D spending ($1.9 bn) is declining as a share of agricultural output and expenditure per farmer represents only 10% of the level in Latin America, a region where $7 bn were invested in 2011. Furthermore, the effectiveness of R&D investments in generating real productivity gains varies widely across regions and is often significantly lower in poorer regions such as Sub-Saharan Africa (Fuglie, 2017). Private R&D investment, at $13 bn in 2011, represents only a quarter of total research investments at a global level but up to three-quarters of spending in developed countries like the US (Fuglie and Toole, 2014). Private investments stimulate new forms of public-private partnerships but remain focused on some particular sectors and technologies (e.g. crop technologies) and remain very limited in the least advanced regions (Fuglie et al., 2019). Increasing public investments could ensure important productivity gains in the future, but need to be sustained over time as their effects typically materialize on time frames of 11 to 30 years (Alston et al., 2011; Baldos et al., 2018). Innovations should also be examined under the broader perspective of their impacts across the full SDG spectrum to ensure that food benefits do no induce some other adverse environmental or socioeconomic trade-offs (Herrero et al., 2021).

Global analyses have compared the costs and benefits of different investment strategies. Rosegrant et al. (2017) compare a wide range of scenario of investment in R&D, as well as water and market infrastructures. They anticipate a need of $8.1 bn per year for R&D investment in developing regions – complemented by $11 bn for water and $23 bn for market infrastructure – to bring population at risk of hunger down from its current level to 361 million in 2050. Examining more ambitious scenarios of investment, they find that with $2–3 bn extra expenditure in R&D, a further 20–25% decrease in undernourishment could be reached at horizon 2030-2050, compared to 6% maximum under more costly investments focused on irrigation or infrastructure. Hertel et al. (2020) compares food security impacts at the horizon 2050 for Africa depending on the level of technological spill-ins versus domestic R&D investment and trade integration (virtual technology import). They find that trade would be the most promising strategy for food security, and spill-ins would remain superior to domestic R&D efforts due to the slow pace of investment and poor performance of R&D institutions in Africa compared to other regions. However, this scenario would only stand if other regions kept using their productivity gains to provide more food instead of sparing natural resources. On the other hand, Burney et al. (2010) estimated that past investments in yield were among the cheapest climate mitigation technology ($4/tCO2 avoided between 1971 and 2005). Looking into the future, Lobell et al. (2013) find that R&D investments targeting adaptation to climate change would also deliver mitigation co-benefits at $11–22/tCO2, thanks to 61 Mha of land conversion savings by 2050. Implementing a similar strategy, Havlík et al. (2013) find that such an approach would be three times more cost-efficient than a carbon tax, also thanks to co-benefits from productivity gains in the livestock sector. A win-win strategy for SDG2 and other environmental goals will therefore depend on the balance found between the different co-benefits accruing from productivity increases.

5.2. International trade and food markets (Target 2.b and 2.c)

The role of market integration and international collaboration on market information is also well acknowledged in SDG2 through Targets 2.b and 2.c. Trade integration can support food security by lowering agricultural product prices and providing easier access to food products (Anderson, 2016; Smith and Glauber, 2019). This is even more important in the context of increased production variability under the threat of climate change extreme events. Examining the role of trade for adaptation, Baldos and Hertel (2015) find for instance that integrating markets could lower undernourishment by up to 100 million by 2050, in the most unfavorable climate scenario. Gouel and Laborde (2021) calculate on their side that welfare losses from climate change are significantly larger (by 30%) when trade adjustments are disabled. Similarly, Janssens et al. (2020) find that undernourishment would increase by 73 million by 2050 under the same assumption of no trade adjustments. Removing tariffs and structural barriers to trade would in contrast reduce undernourishment by 64% compared to the baseline. These benefits hold in general for generic scenarios of trade liberalization, but need of course to be evaluated in the context of each policy situation and trade arrangements, as all scenarios may not be beneficial to all partners without accompanying measures (Bouët et al., 2005; Bureau et al., 2006). Furthermore, benefits of trade cooperation are well recognized in situation of price volatility (Gouel, 2016). Policies like export taxes are particularly detrimental to food security, leading to world price increases and more difficult access to food for importing regions (Bouët and Debucquet, 2011).

On the other hand, international trade could increase environmental pressure if production is relocated to less sustainable areas. Schmitz et al. (2012) finds that increasing trade leads to more deforestation and higher GHG emissions globally, shifting crop production to tropical regions and livestock production to less efficient world regions. And even though international trade could reduce water scarcity globally, it would lead to higher water scarcity in some world regions (Biewald et al., 2014). To limit the environmental impacts of trade liberalization, consistent environmental standards are needed across regions or border-tax adjustments would have to be added in trade agreements to correct for the different emission-intensities and displaced externalities between trading countries.

5.3. Shifting diets

In addition to Targets 2.a-2.c, other impactful measures can also be taken on the demand side to support the transformation of the food systems. Changing our consumption patterns has been recognized for its potential to leverage considerable benefits on SDG outcomes, both by relieving pressure on natural resources as identified in Section 2.2 and fostering the health co-benefits discussed in Section 3.2. Even though no SDG target explicitly calls for dietary changes, Target 12.8 within SDG12 on Responsible production and consumption points to the need to raise awareness for all people about sustainable development and lifestyle in harmony with nature.

Quantification of the impact of dietary shifts has been achieved in many studies to date, some also discussed in Section 3.2. These were initially focusing on the benefits of moving away from meat consumption (Popp et al., 2010; Stehfest et al., 2009; Wirsenius et al., 2010), already highlighting substantial gains in terms of land savings (100 Mha of cropland and 1.1 to 3.2 Gha of pasture land depending on the scenarios for Stehfest et al. and Wirsenius et al.) and for GHG emissions (from 4.8 Gt CO2e in Popp et al. with non-CO2 emissions to 10 Gt CO2e for Stehfest with also land use emissions). These scenarios are often assuming replacing animal proteins by vegetal ones, but a shift from meat towards aquaculture would also bring substantial land sparing effects (Froehlich et al., 2018). More recent studies examined more realistic diet variations: Stehfest et al. (2013) focused on WHO recommendations, Tilman and Clark (2014) distinguished transitions to pescatarian, Mediterranean and vegetarian diets, Ranganathan et al. (2016) compared a broader set of typical diets with different levels of meat cuts and overconsumption reduction, similarly to Springmann et al. (2016a); (2018b) who also consider a healthy or flexitarian option. Beckman et al. (2011) identified in total 83 studies mostly published on the period 2005-2015 assessing environmental benefits of healthy diets. The most influential recent publication on the topic from the EAT-Lancet Commission (Willett et al., 2019) assesses that shifting to a healthier and more sustainable (flexitarian) diet would reduce global emissions by 4.8 Gt CO2e, but do not find any saving in cropland and water consumption due to the extra needs for some specific crops. They also identify that a pescatarian, vegetarian or vegan diet would bring higher benefits including up to 500 Mha land savings. However, as emphasized in Section 3.2, these diets would increase costs for households and would not be affordable for the poorest, indicating the need to move SDG2 together with SDG1.

In addition to shifts to other traditional products, an increasing interest also relates to the potential of "future foods" – composed of products not widely consumed until now, such as insects, algae, cultured meat – to bring new sustainable and healthy options (Parodi et al., 2018). Alexander et al. (2017a) compare the impacts of some of these options for land use and find that the largest benefits would come from the pastureland savings, whereas cultured meat and insects would still require levels of crop inputs similar to chicken eggs. Imitation meat based on vegetal proteins appears the most promising of the options studied and constitute particularly cost-competitive alternatives. Next to food, new products could also be used as feed, likely achieving more rapid acceptance and faster implementation (van Zanten et al., 2015). Pikaar et al. (2018) show a high potential of using microbial protein to substitute protein feeds like soybean cake or cereals, sparing 0 to 13% of cropland, reducing nitrogen losses by 3-8% and land system greenhouse gases by 6–9% depending on the microbial technology. However, the production is rather energy intensive and may shift emissions from the land system to the energy system. More exploratory scenarios based on feed crops replacement by microalgae have also been examined and could lead to large mitigation benefits when the technology becomes mature (Walsh et al., 2015).

5.4. Reducing food waste and losses

Also aligned with SDG12 objectives, reducing inefficiencies along the food supply chain as well as in households and restaurants represent an additional lever for sustainable transformation, explicitly identified in Target 12.3 with the objective of halving food waste per capita and reducing food losses by 2030. The common assumption is over the past decade that one-third of food has been lost or wasted (Gustavsson et al., 2011). More recent refinements allowed estimating the extent of global food losses at 14%, whereas consumer waste would range from 2–17% for cereals to 14–33% for meat and animal products (FAO, 2019). Top-down estimates comparing food caloric supply with population dietary energy needs found global food waste in households to be 20–25% in 2010 (Bodirsky et al., 2020; Hic et al., 2016). Alexander et al. (2017b) also highlight that a large share of the harvested agricultural biomass is also lost in the livestock sector production chain and evaluate that 50% of the energy harvested for food is lost in the food system. Beside food losses, they estimate that overconsumption would be of similar magnitude to consumer waste in terms of inefficiency. van den Bos Verma et al. (2020) also find that waste would be higher than usually assumed and highlight the substantial impact of economic growth on waste rate. Testing for the influence of future economic growth on food waste, Barrera and Hertel (2020) project that it could nearly double at the horizon 2050 without further interventions, while Bodirsky et al. (2020) estimate it will increase by 85% from 2010 until 2050. Considering only a scenario of stabilization of waste at 2020 level would decrease global cropland use by 5% and reduce undernourishment in Sub-Saharan Africa by close to 12% according to their analysis. Hasegawa et al. (2019) – already studied in Section 3.2 for their findings on overconsumption – found similar results from removing food waste, with about 7% for the food calorie savings compared to a reduction of 6% in overconsumption.

5.5. Transformative pathways for the world's food systems

How much could these interventions help to bring food systems onto a sustainable path for SDG2 and the Agenda 2030 in general? We emphasized above the most emblematic transformative actions related to the food systems. There are also more specific mitigation measures are also identified in Section 4. For instance, Smith et al. (2019) present a set of 40 practices that could allow delivering food security, climate mitigation and adaptation, and limiting land degradation and desertification, ranging from increased food productivity or improved cropland or livestock management to demand measures as highlighted above. More general socioeconomic enablers from other SDGs, as identified in Section 3.3, are also key to support the achievement of SDG2.

Combining a large set of these options has usually been presented as the best way – if not the only one – to succeed bringing back the food systems within a safe operating space and providing sustainable food to all while supporting the other SDGs. Table 1 provides an illustration of such comprehensive strategies for the food systems as proposed through policy-oriented reports produced by agencies or expert groups, ranging from the five strategies for the Great Food Transformation from the EAT-Lancet Commission (Willett et al., 2019), to the priority actions from the Global Panel on Agriculture Food Systems for Nutrition (2020). These series of propositions are not similar but contain common recommendations, such as the need to adopt healthier diets or cutting food waste and losses.

Quantification of transformational agendas has been attempted recently through several global modeling

Table 1 Main measures proposed for the food and land systems transformations in selected policy reports

EAT-Lancet Commission (Willet et al., 2019)	Food and Land Use Coalition (FOLU, 2019)	CGIAR CCAFS (Steiner et al., 2020)	Global Panel on Agriculture and Food Systems for Nutrition (2020)
"Five strategies for a Great Food Transformation"	*"Ten critical transitions"*	*"Actions to transforms food systems"*	*"Priority policy actions to transition food systems towards sustainable healthy diets"**
1. seek international and national commitments to shift towards healthy diets	1. healthy diets	1. no ag land expansion into high carbon land	1a. rebalance agricultural subsidies
2. reorient agricultural priorities from producing large quantities of food to producing healthy food	2. productive and regenerative agriculture	2. support development of climate-resilient and low emissions practices	1b. rebalance agricultural R&D
3. sustainably intensify food production, generating high-quality output	3. protecting and restoring nature	3. support prosperity through rural reinvigoration	1c. promote production of a wide range of nutrient-rich food
4. strong and coordinated governance of land and oceans	4. healthy and productive ocean	4. early warning and safety nets	2a. coopt levers of trade
5. Halve food loss and waste, in line with global SDGs	5. diversifying protein chain	5. help farmers make better choice	2b. cut food loss and waste
	6. reducing food losses and waste	6. shift to heathy and sustainable diets	2c. support job growth across the food system
	7. local loops and linkages	7. reduce food losses and waste	2d. support technology and financial innovation along food supply chains
	8. digital revolution	8. implement policy and institutional change for transformations	3a. implement safety nets
	9. stronger rural livelihoods	9. unlock billions in sustainable finance	3b. promote pro-poor growth
	10. gender and demography	10. drive social change to more sustainable decisions	3c. reduce costs through tech and innovation
		11. transform innovation systems	3d. adjust tax and subsidies on key foods
			4a. define principles of engagement between public and private sector
			4b. upgrade dietary guidelines and promote enhanced knowledge about implication of dietary choices
			4c. better regulate advertising and marketing
			4d. implement behavioral nudges via carefully designed taxes and subsidies

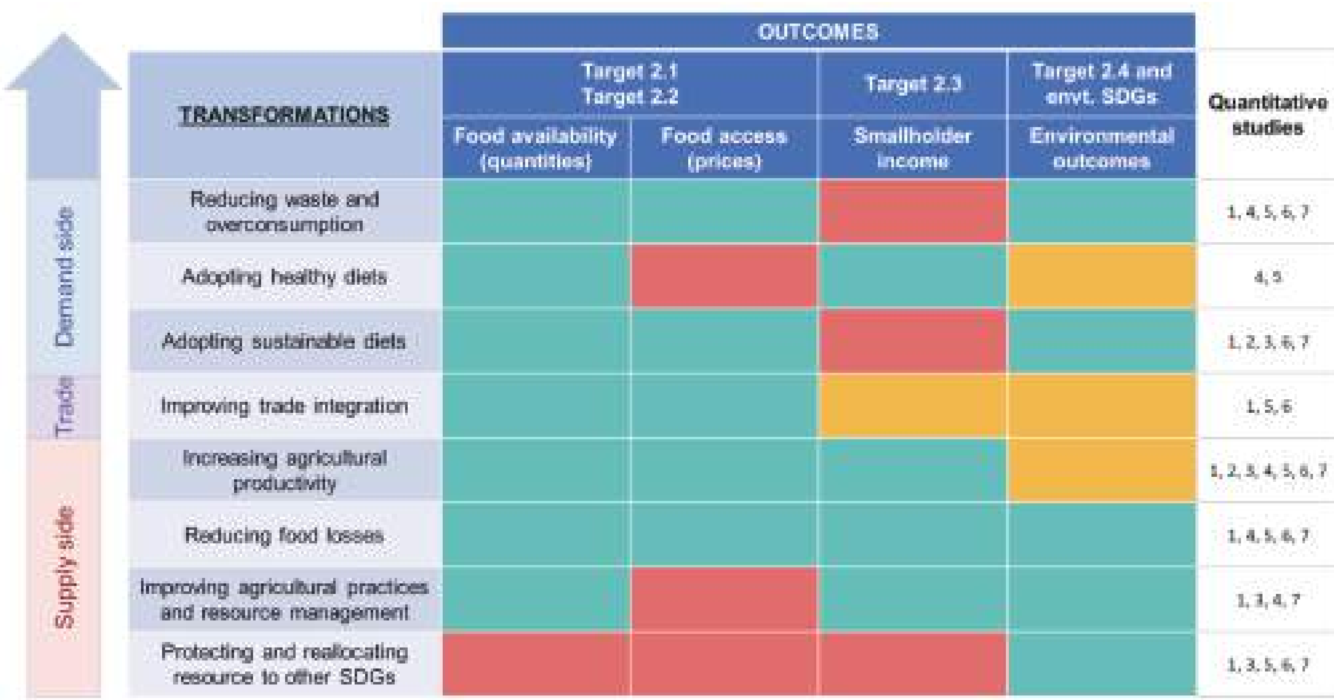
* For the Global Panel on Agriculture Food Security and Nutrition's report, the actions are structured around 4 axes, identified here with the following numbering: 1 – availability; 2 – accessibility; 3 – affordability; 4 – desirability (see report Figure 9.2).

studies. In contrast to most studies presented in previous sections, these typically model in a forward-looking approach the combination of many different simultaneous interventions into the food systems, to see to what extent these can together help achieve the various sustainable development dimensions. We identified here seven studies corresponding to this description: four based on integrated assessment models (Deppermann et al., 2019; Obersteiner et al., 2016; Springmann et al., 2018a; van Vuuren et al., 2015), two land systems analyses (Erb et al., 2016; Gerten et al., 2020) and one model ensemble study, with a stronger emphasis on biodiversity (Leclère et al., 2020).

Figure 5 below provides an overview of the typical transformations which have been modeled across these different studies. For each of these transformations, we highlight whether these would enhance specific indicators supporting the different SDG2 targets. All of the measures for instance improve food availability except for the supply side interventions aimed at allocating more resources to other SDGs. In contrast, adopting healthy diets may increase the cost of food, and therefore complicate food access, whereas sustainable diet based on moving away from meat proteins can be done at a low price by using vegetal proteins. Food access may also be challenged by more sustainable management practices, which may also come with extra production costs. When looking at smallholder income, approaches leading to lower food demand through efficiency gains in the supply chain may paradoxically decrease producer prices and smallholder revenues. Last, some transformation may also be ambiguous for the environment: trade integration for the reasons discussed above (Section 5.2), agricultural productivity gains due to the Jevons paradox, and healthy diets due to their increased demand in specific nutrient-rich products such as fruits, vegetables and nuts, dairy, etc. As can be seen, not many transformations are win-wins across all dimensions. Reducing food losses is one of them when harvest losses are included and avoidable at low cost for the producer. Some options can be combined, e.g. sustainable and healthy diets could be designed to deliver positive outcomes across all dimensions.

These studies of food system transformation highlight the need for combining a large number of options on both the supply and demand sides to achieve sustainable pathways. The challenge for the food systems modeling community in the future will be to enrich these analyses of alternative sustainable pathways and implement these in a national and local con-

Figure 5 Key transformations implemented in global analyses and their typical impact for relevant indicators: green = positive impact, red = negative impact, orange = ambiguous impact. The impacts are based on typical impact of the market equilibrium model responses, but the measures are not tested separately in each of the studies. For smallholder income, the impact is based on the anticipated average farm income effect.
Study references: 1 - Vuuren et al. (2015); 2 - Erb et al. (2016); 3 - Obersteiner et al. (2016); 4 - Willet et al. (2019) / Springmann et al. (2018); 5 – Deppermann et al. (2019); 6 - Leclere et al. (2020); 7 - Gerten et al. (2020)



text (Schmidt-Traub et al., 2019). This endeavor will be even more important now that the COVID-19 crisis has brought new social and economic challenges that could undermine the achievement of SDGs and limit progress towards long-term sustainability. Revisiting the current frameworks and analyzing how to overcome these challenges in an integrative manner should be high priority for the years to come, while also paying greater attention to questions of vulnerability and resilience.

REFERENCES

1. Afshin, A., Sur, P.J., Fay, K.A., Cornaby, L., Ferrara, G., Salama, J.S., Mullany, E.C., ..., Murray, C.J.L. (2019) Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet 393, 1958–1972.
2. Agarwal, B. (2018) Gender equality, food security and the sustainable development goals. Current Opinion in Environmental Sustainability 34, 26–32.
3. Ahmed, N., Thompson, S., Glaser, M. (2018) Global Aquaculture Productivity, Environmental Sustainability, and Climate Change Adaptability. Environmental Management 63, 159–172.
4. Alavanja, M.C.R., Hoppin, J.A., Kamel, F. (2004) Health effects of chronic pesticide exposure: cancer and neurotoxicity. Annu. Rev. Public Health 25, 155–197.
5. Alcott, B. (2005) Jevons' paradox. Ecological Economics 54, 9–21.
6. Alderman, H., Headey, D.D. (2017) How Important is Parental Education for Child Nutrition? World Development 94, 448–464.
7. Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., Rounsevell, M.D.A. (2017a) Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? Global Food Security 15, 22–32.
8. Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., Rounsevell, M.D.A. (2017b) Losses, inefficiencies and waste in the global food system. Agricultural Systems 153, 190–200.
9. Alexandratos, N., Bruinsma, J., (2012) World Agriculture Towards 2030/2050: The 2012 Revision. Food and Agriculture Organization of the United Nations, Rome.
10. Alston, J.M., Andersen, M.A., James, J.S., Pardey, P.G. (2011) The Economic Returns to U.S. Public Agricultural Research. American Journal of Agricultural Economics 93, 1257–1277.
11. Anderson, K. (2016) Agricultural trade, policy reforms, and global food security. Springer.
12. Baldos, U.L.C., Hertel, T.W. (2014) Global food security in 2050: the role of agricultural productivity and climate change. Australian Journal of Agricultural and Resource Economics 58, 554–570.
13. Baldos, U.L.C., Hertel, T.W. (2015) The role of international trade in managing food security risks from climate change. Food Security 7, 275–290.
14. Baldos, U.L.C., Viens, F.G., Hertel, T.W., Fuglie, K.O. (2018) R&D Spending, Knowledge Capital, and Agricultural Productivity Growth: A Bayesian Approach. American Journal of Agricultural Economics 101, 291–310.
15. Balmford, A., Green, R.E., Scharlemann, J.P.W. (2005) Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. Global Change Biology 11, 1594–1605.
16. Barbier, E.B., Hochard, J.P. (2018) Land degradation and poverty. Nature Sustainability 1, 623–631.
17. Barrera, E.L., Hertel, T. (2020) Global food waste across the income spectrum: Implications for food prices, production and resource use. Food Policy, 101874.
18. Barrett, C., Reardon, T., Swinnen, J., Zilberman, D., (2019) Structural transformation and economic development: insights from the agri-food value chain revolution. Cornell University.
19. Barthel, S., Isendahl, C., Vis, B.N., Drescher, A., Evans, D.L., van Timmeren, A. (2019) Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. The Anthropocene Review 6, 71–97.
20. Beach, R.H., Sulser, T.B., Crimmins, A., Cenacchi, N., Cole, J., Fukagawa, N.K., Mason-DCroz, D., Myers, S., Sarofim, M.C., Smith, M., Ziska, L.H. (2019) Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. The Lancet Planetary Health 3, e307–e317.
21. Beckman, J., Jones, C.A., Sands, R. (2011) A global general equilibrium analysis of biofuel mandates and greenhouse gas emissions. American Journal of Agricultural Economics 93, 334–341.
22. Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., Williams, M. (2015) Feeding 9 billion by 2050 } Putting fish back on the menu. Food Security 7, 261–274.
23. Biewald, A., Rolinski, S., Lotze-Campen, H., Schmitz, C., Dietrich, J.P. (2014) Valuing the impact of trade on local blue water. Ecological Economics 101, 43–53.
24. Bijl, D.L., Bogaart, P.W., Dekker, S.C., Stehfest, E., de Vries, B.J.M., van Vuuren, D.P. (2017) A physical-

ly-based model of long-term food demand. Global Environmental Change 45, 47–62.
25. Black, R.E., Victora, C.G., Walker, S.P., Bhutta, Z.A., Christian, P., de Onis, M., Ezzati, M., Grantham-McGregor, S., Katz, J., Martorell, R., Uauy, R. (2013) Maternal and child undernutrition and overweight in low-income and middle-income countries. The Lancet 382, 427–451.
26. Bodirsky, B.L., Dietrich, J.P., Martinelli, E., Stenstad, A., Pradhan, P., Gabrysch, S., Mishra, A., Weindl, I., Mouël, C.L., Rolinski, S., Baumstark, L., Wang, X., Waid, J.L., Lotze-Campen, H., Popp, A. (2020) The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. Scientific Reports 10.
27. Bodirsky, B.L., Popp, A., Lotze-Campen, H., Dietrich, J.P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M., Humpenöder, F., Biewald, A., Stevanovic, M. (2014) Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. Nature Communications 5, -.
28. Bodirsky, B.L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., Lotze-Campen, H. (2015) Global Food Demand Scenarios for the 21<italic>st</italic> Century. PLoS ONE 10, e0139201.
29. Böhringer, C., Löschel, A. (2006) Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. Ecological Economics 60, 49–64.
30. Bonsch, M., Popp, A., Biewald, A., Rolinski, S., Schmitz, C., Weindl, I., Stevanovic, M., Högner, K., Heinke, J., Ostberg, S., Dietrich, J.P., Bodirsky, B., Lotze-Campen, H., Humpenöder, F. (2015) Environmental flow provision: Implications for agricultural water and land-use at the global scale. Global Environmental Change 30, 113–132.
31. Borlaug, N.E. (2002) Feeding a world of 10 billion people: the miracle ahead. In Vitro Cellular & Developmental Biology. Plant 38, 221–228.
32. Bouët, A., Bureau, J.-C., Decreux, Y., Jean, S. (2005) Multilateral Agricultural Trade Liberalisation: The Contrasting Fortunes of Developing Countries in the Doha Round. The World Economy 28, 1329–1354.
33. Bouët, A., Debucquet, D.L. (2011) Food crisis and export taxation: the cost of non-cooperative trade policies. Review of World Economics 148, 209–233.
34. Bouwman, L., Goldewijk, K.K., Hoek, K.W.V.D., Beusen, A.H.W., Vuuren, D.P.V., Willems, J., Rufino, M.C., Stehfest, E. (2011) Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. Proceedings of the National Academy of Sciences 110, 20882–20887.
35. Brauman, K.A., Siebert, S., Foley, J.A. (2013) Improvements in crop water productivity increase water sustainability and food security}a global analysis. Environmental Research Letters 8, 024030.
36. Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C. (2016) Future urban land expansion and implications for global croplands. Proceedings of the National Academy of Sciences 114, 8939–8944.
37. Burchi, F., Fanzo, J., Frison, E. (2011) The Role of Food and Nutrition System Approaches in Tackling Hidden Hunger. International Journal of Environmental Research and Public Health 8, 358–373.
38. Bureau, J.-C., Jean, S., Matthews, A. (2006) The consequences of agricultural trade liberalization for developing countries: distinguishing between genuine benefits and false hopes. World Trade Review 5, 225–249.
39. Burney, J.A., Davis, S.J., Lobell, D.B. (2010) Greenhouse gas mitigation by agricultural intensification. Proceedings of the National Academy of Sciences 107, 12052–12057.
40. Busch, J., Ferretti-Gallon, K. (2017) What drives deforestation and what stops it? A meta-analysis. Review of Environmental Economics and Policy 11, 3–23.
41. Byerlee, D., Stevenson, J., Villoria, N. (2014) Does intensification slow crop land expansion or encourage deforestation? Global Food Security 3, 92–98.
42. Byers, E., Gidden, M., Leclre, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., Parkinson, S., Rao, N.D., Rogelj, J., Satoh, Y., Wada, Y., Willaarts, B., Riahi, K. (2018) Global exposure and vulnerability to multi-sector development and climate change hotspots. Environmental Research Letters 13, 055012.
43. Cabral, R.B., Bradley, D., Mayorga, J., Goodell, W., Friedlander, A.M., Sala, E., Costello, C., Gaines, S.D. (2020) A global network of marine protected areas for food. Proceedings of the National Academy of Sciences 117, 28134–28139.
44. Cafiero, C., Melgar-Quinonez, H.R., Ballard, T.J., Kepple, A.W. (2014) Validity and reliability of food security measures. Annals of the New York Academy of Sciences 1331, 230–248.
45. Carpenter, S.R., Bennett, E.M. (2011) Reconsideration of the planetary boundary for phosphorus. Environmental Research Letters 6, 014009.
46. Chaudhary, A., Kastner, T. (2016) Land use biodiversity impacts embodied in international food trade. Global Environmental Change 38, 195–204.

47. Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L., Hill, J.D. (2020) Global food system emissions could preclude achieving the 1.5} and 2}C climate change targets. Science 370, 705–708.
48. Coker, R., Rushton, J., Mounier-Jack, S., Karimuribo, E., Lutumba, P., Kambarage, D., Pfeiffer, D.U., Stärk, K., Rweyemamu, M. (2011) Towards a conceptual framework to support one-health research for policy on emerging zoonoses. The Lancet Infectious Diseases 11, 326–331.
49. Creutzig, F., d'Amour, C.B., Weddige, U., Fuss, S., Beringer, T., Gläser, A., Kalkuhl, M., Steckel, J.C., Radebach, A., Edenhofer, O. (2019) Assessing human and environmental pressures of global land-use change 2000-2010. Global Sustainability 2.
50. Creutzig, F., Popp, A., Plevin, R., Luderer, G., Minx, J., Edenhofer, O. (2012) Reconciling top-down and bottom-up modelling on future bioenergy deployment. Nature Climate Change 2, 320–327.
51. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2, 198–209.
52. Cunningham, S.A., Attwood, S.J., Bawa, K.S., Benton, T.G., Broadhurst, L.M., Didham, R.K., McIntyre, S., Perfecto, I., Samways, M.J., Tscharntke, T., Vandermeer, J., Villard, M.-A.e., ,, Young, A.G., Lindenmayer, D.B. (2013) To close the yield-gap while saving biodiversity will require multiple locally relevant strategies. Agriculture, Ecosystems & Environment 173, 20–27.
53. de Lima, C.Z., Buzan, J.R., Moore, F.C., Baldos, U.L.C., Huber, M., Hertel, T.W. (2021) Heat stress on agricultural workers exacerbates crop impacts of climate change. Environmental Research Letters 16, 044020.
54. de Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P. (2013) Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Current Opinion in Environmental Sustainability 5, 392–402.
55. Deguines, N., Jono, C., Baude, M., Henry, M., Julliard, R., Fontaine, C. (2014) Large-scale trade-off between agricultural intensification and crop pollination services. Frontiers in Ecology and the Environment 12, 212–217.
56. Deppermann, A., Valin, H., Gusti, M., Sperling, F., Batka, M., Chang, J., Frank, S., Havlik, P., Lauri, P., Leclere, D., Palazzo, A., Thomson, M., Obersteiner, M., (2019) Towards sustainable food and land-use systems: Insights from integrated scenarios of the Global Biosphere Management Model (GLOBIOM). International Institute for Applied Systems Analysis, Laxenburg, Austria.
57. Dixon, P.B., Parmenter, B.R., (1996) Chapter 1 Computable general equilibrium modelling for policy analysis and forecasting, Handbook of Computational Economics. Elsevier, 3–85.
58. Donald, P.F., Green, R.E., Heath, M.F. (2001) Agricultural intensification and the collapse of Europe}s farmland bird populations. Proceedings of the Royal Society of London. Series B: Biological Sciences 268, 25–29.
59. Eickhout, B., Bouwman, A., Vanzeijts, H. (2006) The role of nitrogen in world food production and environmental sustainability. Agriculture, Ecosystems & Environment 116, 4–14.
60. Eitelberg, D.A., Vliet, J., Verburg, P.H. (2014) A review of global potentially available cropland estimates and their consequences for model-based assessments. Global Change Biology 21, 1236–1248.
61. Endo, A., Tsurita, I., Burnett, K., Orencio, P.M. (2015) A review of the current state of research on the water, energy, and food nexus. Journal of Hydrology: Regional Studies.
62. Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H. (2016) Exploring the biophysical option space for feeding the world without deforestation. Nature Communications.
63. Ericksen, P.J. (2008) Conceptualizing food systems for global environmental change research. Global Environmental Change 18, 234–245.
64. Evans, A.E.V., Mateo-Sagasta, J., Qadir, M., Boelee, E., Ippolito, A. (2019) Agricultural water pollution: key knowledge gaps and research needs. Current Opinion in Environmental Sustainability 36, 20–27.
65. Ewers, R.M., Scharlemann, J.P.W., Balmford, A., Green, R.E. (2009) Do increases in agricultural yield spare land for nature? Global Change Biology 15, 1716–1726.
66. Ewing, M., Msangi, S. (2009) Biofuels production in developing countries: assessing tradeoffs in welfare and food security. Environmental Science & Policy 12, 520–528.
67. FAO (1996) Rome Declaration on World Food Security and World Food Summit Plan of Action. Food and Agriculture Organization of the United Nations.
68. FAO (2011) The State of Food and Agriculture: Women in Agriculture Closing the gender gap for development. Food and Agriculture Organization of The United Nations, Roma.
69. FAO (2018) The Future of Food and Agriculture 2018: Alternative Pathways to 2050. Food and Agriculture Food and Agriculture Organization of the United Nations.
70. FAO (2019) The State of Food and Agriculture: Moving Forward on Food Loss and Waste Reduc-

tion. Food and Agriculture Organization of the United Nations, Rome.

71. FAO (2020a) The State of Food and Agriculture: Overcoming water challenges in agriculture. Food and Agriculture Organization of the United Nations, Rome.
72. FAO (2020b) The State of World Fisheries and Aquaculture 2020. Sustainability in Action. Food and Agriculture Organization of The United Nations, Rome.
73. FAO, IFAD, UNICEF, WFP, WHO (2017) The State of Food Security and Nutrition in the World 2017: Building Resilience for Peace and Food Security. Food and Agriculture Organization of the United Nations, Rome.
74. FAO, IFAD, UNICEF, WFP, WHO, (2020) The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets. Food and Agriculture Organization of the United Nations.
75. Field, C.B., Mach, K.J. (2017) Rightsizing carbon dioxide removal. Science 356, 706–707.
76. Fischer, R.A., Byerlee, D., Edmeades, G.O., (2009) Can Technology Deliver on the Yield Challenge to 2050? Food and Agriculture Organization of the United Nations.
77. Fitton, N., Alexander, P., Arnell, N., Bajzelj, B., Calvin, K., Doelman, J., Gerber, J.S., Havlik, P., Hasegawa, T., Herrero, M., Krisztin, T., van Meijl, H., Powell, T., Sands, R., Stehfest, E., West, P.C., Smith, P. (2019) The vulnerabilities of agricultural land and food production to future water scarcity. Global Environmental Change 58, 101944.
78. Folberth, C., Khabarov, N., Balkovic, J., Skalsky, R., Visconti, P., Ciais, P., Janssens, I.A., Penuelas, J., Obersteiner, M. (2020) The global cropland-sparing potential of high-yield farming. Nature Sustainability 3, 281–289.
79. Foley, J.A., Prentice, I.C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., Haxeltine, A. (1996) An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. Global Biogeochemical Cycles 10, 603–628.
80. Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., others (2011) Solutions for a cultivated planet. Nature 478, 337–342.
81. Food and Land Use Coalition (2019) Growing Better: Ten Critical Transformations to Transform Food and Land Use. Food and Land Use Coalition.
82. Frank, S., Beach, R., Havlik, P., Valin, H., Herrero, M., Mosnier, A., Hasegawa, T., Creason, J., Ragnauth, S., Obersteiner, M. (2018a) Structural change as a key component for agricultural non-CO2 mitigation efforts. Nature Communications 9.
83. Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M., Smith, P., Hasegawa, T., Kraxner, F., Obersteiner, M. (2017) Reducing greenhouse gas emissions in agriculture without compromising food security? Environmental Research Letters.
84. Frank, S., Havlik, P., Stehfest, E., van Meijl, H., Witzke, P., Perez-Dominguez, I., van Dijk, M., Doelman, J.C., Fellmann, T., Koopman, J.F.L., Tabeau, A., Valin, H. (2018b) Agricultural non-CO2 emission reduction potential in the context of the 1.5 C target. Nature Climate Change.
85. Fritz, S., See, L., van der Velde, M., Nalepa, R.A., Perger, C., Schill, C., McCallum, I., Schepaschenko, D., Kraxner, F., Cai, X., Zhang, X., Ortner, S., Hazarika, R., Cipriani, A., Di Bella, C., Rabia, A.H., Garcia, A., Vakolyuk, M.y., Singha, K., Beget, M.E., Erasmi, S., Albrecht, F., Shaw, B., Obersteiner, M. (2013) Downgrading Recent Estimates of Land Available for Biofuel Production. Environmental science & technology 47, 1688–1694.
86. Froehlich, H.E., Runge, C.A., Gentry, R.R., Gaines, S.D., Halpern, B.S. (2018) Comparative terrestrial feed and land use of an aquaculture-dominant world. Proceedings of the National Academy of Sciences 115, 5295–5300.
87. Fuglie, K. (2017) R&D Capital, R&D Spillovers, and Productivity Growth in World Agriculture. Applied Economic Perspectives and Policy 40, 421–444.
88. Fuglie, K., Gautam, M., Goyal, A., Maloney, W.F. (2019) Harvesting prosperity: Technology and productivity growth in agriculture. The World Bank.
89. Fuglie, K.O., (2010) Total Factor Productivity in the Global Agricultural Economy: Evidence from FAO Data, in: Alston, J.M., Babcock, B.A., Pardey, P.G. (Eds.), The Shifting Patterns of Agricultural Production and Productivity Worldwide. Midwest Agribusiness Trade Research and Iowa State University, Ames, IA, 63–95.
90. Fuglie, K.O., Toole, A.A. (2014) The Evolving Institutional Structure of Public and Private Agricultural Research. American Journal of Agricultural Economics 96, 862–883.
91. Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B.L., Bosetti, V., Callen, J., Despres, J., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Havlik, P., Humpenöder, F., Koopman, J.F.L., van Meijl, H., Ochi, Y., Popp, A., Schmitz, A., Takahashi, K., van Vuuren, D. (2019) A multi-model assessment of food security implications of climate change mitigation. Nature Sustainability 2, 386–396.
92. Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B.L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rock-

ström, J., Schaphoff, S., Schellnhuber, H.J. (2020) Feeding ten billion people is possible within four terrestrial planetary boundaries. Nature Sustainability 3, 200–208.
93. Giannadaki, D., Giannakis, E., Pozzer, A., Lelieveld, J. (2018) Estimating health and economic benefits of reductions in air pollution from agriculture. Science of The Total Environment 622–623, 1304–1316.
94. Gibb, R., Redding, D.W., Chin, K.Q., Donnelly, C.A., Blackburn, T.M., Newbold, T., Jones, K.E. (2020) Zoonotic host diversity increases in human-dominated ecosystems. Nature 584, 398–402.
95. Global Panel on Agriculture Food Systems for Nutrition (2020) Future Food Systems: For people, our planet, and prosperity.
96. Golden, C.D., Allison, E.H., Cheung, W.W.L., Dey, M.M., Halpern, B.S., McCauley, D.J., Smith, M., Vaitla, B., Zeller, D., Myers, S.S. (2016) Nutrition: Fall in fish catch threatens human health. Nature 534, 317–320.
97. Golub, A., Hertel, T., Lee, H.-L., Rose, S., Sohngen, B. (2009) The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. Resource and Energy Economics 31, 299–319.
98. Golub, A.A., Henderson, B.B., Hertel, T.W., Gerber, P.J., Rose, S.K., Sohngen, B. (2012) Global climate policy impacts on livestock, land use, livelihoods, and food security. Proceedings of the National Academy of Sciences.
99. Gomez, M.I., Barrett, C.B., Raney, T., Pinstrup-Andersen, P., Meerman, J., Croppenstedt, A., Carisma, B., Thompson, B. (2013) Post-green revolution food systems and the triple burden of malnutrition. Food Policy 42, 129–138.
100. Gouel, C. (2016) Trade policy coordination and food price volatility. American Journal of Agricultural Economics 98, 1018–1037.
101. Gouel, C., Guimbard, H. (2018) Nutrition Transition and the Structure of Global Food Demand. American Journal of Agricultural Economics 101, 383–403.
102. Gouel, C., Laborde, D. (2021) The crucial role of domestic and international market-mediated adaptation to climate change. Journal of Environmental Economics and Management 106, 102408.
103. Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G. (2018) The paradox of irrigation efficiency. Science 361, 748–750.
104. Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S.D., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlk, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H. (2018) A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. Nature Energy 3, 515–527.
105. Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., (2011) Global food losses and food waste. Food and Agriculture Organization of the United Nations.
106. Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M. (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences 104, 12942–12947.
107. Hallegatte, S., Rozenberg, J. (2017) Climate change through a poverty lens. Nature Climate Change 7, 250–256.
108. Hasegawa, T., Fujimori, S., Havlik, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Dominguez, I.P., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.-J., Wiebe, K., Witzke, P. (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change 8, 699–703.
109. Hasegawa, T., Fujimori, S., Takahashi, K., Masui, T. (2015) Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. Environmental Research Letters 10, 014010.
110. Hasegawa, T., Fujimori, S., Takahashi, K., Yokohata, T., Masui, T. (2016) Economic implications of climate change impacts on human health through undernourishment. Climatic Change 136, 189–202.
111. Hasegawa, T., Havlik, P., Frank, S., Palazzo, A., Valin, H. (2019) Tackling food consumption inequality to fight hunger without pressuring the environment. Nature Sustainability 2, 826–833.
112. Hasegawa, T., Sands, R.D., Brunelle, T., Cui, Y., Frank, S., Fujimori, S., Popp, A. (2020) Food security under high bioenergy demand toward long-term climate goals. Climatic Change 163, 1587–1601.
113. Havlík, P., Valin, H., Gusti, M., Schmid, E., Leclère, D., Forsell, N., Herrero, M., Khabarov, N., Mosnier, A., Cantele, M., Obersteiner, M., (2015) Climate change impacts and mitigation in the developing world: An integrated assessment of the agriculture and forestry sectors. World Bank.

114. Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A. (2014) Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences 111, 3709–3714.
115. Havlík, P., Valin, H., Mosnier, A., Obersteiner, M., Baker, J.S., Herrero, M., Rufino, M.C., Schmid, E. (2013) Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. American Journal of Agricultural Economics 95, 442–448.
116. Headey, D.D., Martin, W.J. (2016) The Impact of Food Prices on Poverty and Food Security. Annual Review of Resource Economics 8, 329–351.
117. Heinke, J., Lannerstad, M., Gerten, D., Havlik, P., Herrero, M., Notenbaert, A.M.O., Hoff, H., Müller, C. (2020) Water Use in Global Livestock Production}Opportunities and Constraints for Increasing Water Productivity. Water Resources Research 56.
118. Henders, S., Persson, U.M., Kastner, T. (2015) Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. Environmental Research Letters 10, 125012.
119. Henderson, B., Golub, A., Pambudi, D., Hertel, T., Godde, C., Herrero, M., Cacho, O., Gerber, P. (2017) The power and pain of market-based carbon policies: a global application to greenhouse gases from ruminant livestock production. Mitigation and Adaptation Strategies for Global Change 23, 349–369.
120. Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M. (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences 110, 20888–20893.
121. Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C., Dizyee, K., Folberth, C., Godde, C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C. (2020) Innovation can accelerate the transition towards a sustainable food system. Nature Food 1, 266–272.
122. Herrero, M., Thornton, P.K., Mason-DCroz, D., Palmer, J., Bodirsky, B.L., Pradhan, P., Barrett, C.B., Benton, T.G., Hall, A., Pikaar, I., Bogard, J.R., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Fanzo, J., Godde, C.M., Jarvis, A., Loboguerrero, A.M., Mathys, A., McIntyre, C.L., Naylor, R.L., Nelson, R., Obersteiner, M., Parodi, A., Popp, A., Ricketts, K., Smith, P., Valin, H., Vermeulen, S.J., Vervoort, J., van Wijk, M., van Zanten, H.H.E., West, P.C., Wood, S.A., Rockström, J. (2021) Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health 5, e50–e62.
123. Hertel, T., (2012a) Global Applied General Equilibrium Analysis using the GTAP Framework. Global Trade Analysis Project (GTAP), Department of Agricultural Economics, Purdue University, West Lafayette, IN.
124. Hertel, T.W. (1997) Global Trade Analysis: modeling and applications. Cambridge University Press.
125. Hertel, T.W., (2012b) Implications of Agricultural Productivity for Global Cropland Use and GHG Emissions: Borlaug vs. Jevons. Global Trade Analysis Project Center.
126. Hertel, T.W. (2015) Food security under climate change. Nature Climate Change 6, 10–13.
127. Hertel, T.W., Baldos, U.L.C., van der Mensbrugghe, D. (2016) Predicting Long-Term Food Demand, Cropland Use, and Prices. Annual Review of Resource Economics 8, 417–441.
128. Hertel, T.W., Burke, M.B., Lobell, D.B. (2010) The poverty implications of climate-induced crop yield changes by 2030. Global Environmental Change 20, 577–585.
129. Hertel, T.W., Ramankutty, N., Baldos, U.L.C. (2014) Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. Proceedings of the National Academy of Sciences 111, 13799–13804.
130. Hertel, T.W., Rose, S.K., Tol, R.S.J. (2009) Economic Analysis of Land Use in Global Climate Change Policy. Routledge.
131. Hertel, T.W., Steinbuks, J., Baldos, U.L.C., (2012) Competition for Land in the Global Bioeconomy, 2012 Conference, August 18-24, 2012, Foz do Iguacu, Brazil.
132. Hic, C., Pradhan, P., Rybski, D., Kropp, J.P. (2016) Food Surplus and Its Climate Burdens. Environmental science & technology 50, 4269–4277.
133. Hicks, C.C., Cohen, P.J., Graham, N.A.J., Nash, K.L., Allison, E.H., D'Lima, C., Mills, D.J., Roscher,

M., Thilsted, S.H., Thorne-Lyman, A.L., MacNeil, M.A. (2019) Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574, 95–98.
134. Hirvonen, K., Bai, Y., Headey, D., Masters, W.A. (2019) Affordability of the EAT}Lancet reference diet: a global analysis. The Lancet Global Health.
135. Hiza, H.A.B., Casavale, K.O., Guenther, P.M., Davis, C.A. (2013) Diet Quality of Americans Differs by Age, Sex, Race/Ethnicity, Income, and Education Level. Journal of the Academy of Nutrition and Dietetics 113, 297–306.
136. HLPE (2017) Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.
137. HLPE (2020) Food security and nutrition: building a global narrative towards 2030. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Insecurity.
138. IAASTD (2009) International assessment of agricultural knowledge, science and technology for development (IAASTD).
139. Ingram, J. (2011) A food systems approach to researching food security and its interactions with global environmental change. Food Security 3, 417–431.
140. IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.
141. IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC, Switzerland.
142. IPCC (2019) Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Switzerland.
143. IRENA, (2020) Global Renewable Energy Outlook: Energy Transformations 2050. International Renewable Energy Agency.
144. ISC (2017) A Guide to SDG Interactions: from Science to Implementation. International Council for Science, Paris.
145. Ivanic, M., Martin, W., (2014) Short-and long-run impacts of food price changes on poverty.
146. Ivanic, M., Martin, W., Zaman, H. (2012) Estimating the Short-Run Poverty Impacts of the 2010–11 Surge in Food Prices. World Development 40, 2302–2317.
147. Janssens, C., Havlik, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclere, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Lipzig, N.V., Maertens, M. (2020) Global hunger and climate change adaptation through international trade. Nature Climate Change.
148. Jones, B.A., Grace, D., Kock, R., Alonso, S., Rushton, J., Said, M.Y., McKeever, D., Mutua, F., Young, J., McDermott, J., Pfeiffer, D.U. (2013) Zoonosis emergence linked to agricultural intensification and environmental change. Proceedings of the National Academy of Sciences 110, 8399–8404.
149. Jung, M., Rowhani, P., Scharlemann, J.P.W. (2019) Impacts of past abrupt land change on local biodiversity globally. Nature Communications 10.
150. Kanter, D.R., Winiwarter, W., Bodirsky, B.L., Bouwman, L., Boyer, E., Buckle, S., Compton, J.E., Dalgaard, T., de Vries, W., Lecl\`e, re, David, Leip, A., Müller, C., Popp, A., Raghuram, N., Rao, S., Sutton, M.A., Tian, H., Westhoek, H., Zhang, X., Zurek, M. (2020) A framework for nitrogen futures in the shared socioeconomic pathways. Global Environmental Change 61, 102029.
151. Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S. (2012) Global changes in diets and the consequences for land requirements for food. Proceedings of the National Academy of Sciences 109, 6868–6872.
152. Kearney, J. (2010) Food consumption trends and drivers. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2793–2807.
153. Kerwath, S.E., Winker, H., Götz, A., Attwood, C.G. (2013) Marine protected area improves yield without disadvantaging fishers. Nature Communications 4.
154. Keyzer, M.A., Merbis, M.D., Pavel, I.F.P.W., van Wesenbeeck, C.F.A. (2005) Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? Ecological Economics 55, 187–202.
155. Kim, H., Rosa, I.M.D., Alkemade, R., Leadley, P., Hurtt, G., Popp, A., van Vuuren, D.P., Anthoni, P., Arneth, A., Baisero, D., Caton, E., Chaplin-Kramer, R., Chini, L., Palma, A.D., Fulvio, F.D., Marco, M.D., Espinoza, F., Ferrier, S., Fujimori, S., Gonzalez, R.E., Gueguen, M., Guerra, C., Harfoot, M., Harwood, T.D., Hasegawa, T., Haverd, V., Havl\'\i, k, Petr, Hellweg, S., Hill, S.L.L., Hirata, A., Hoskins, A.J., Janse, J.H., Jetz, W., Johnson, J.A., Krause, A., Lecl\`e, re, David, Martins, I.S., Matsui, T., Merow, C., Obersteiner, M., Ohashi, H., Poulter, B., Purvis, A., Quesada, B., Rondinini, C., Schipper, A.M., Sharp, R., Takahashi, K., Thuiller, W., Titeux, N.,

Visconti, P., Ware, C., Wolf, F., Pereira, H.M. (2018) A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios. Geoscientific Model Development 11, 4537–4562.
156. Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S., Beach, R. (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America 105, 10302–10307.
157. Kreidenweis, U., Humpenöder, F., Stevanovic, M., Bodirsky, B.L., Kriegler, E., Lotze-Campen, H., Popp, A. (2016) Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. Environmental Research Letters 11, 085001.
158. Laborde, D., Martin, W., Swinnen, J., Vos, R. (2020) COVID-19 risks to global food security. Science 369, 500–502.
159. Laborde Debucquet, D., Martin, W. (2018) Implications of the global growth slowdown for rural poverty. Agricultural Economics 49, 325–338.
160. Lal, R. (2009) Soil degradation as a reason for inadequate human nutrition. Food Security 1, 45–57.
161. Lal, R. (2010) Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security 2, 169–177.
162. Lal, R. (2015) Restoring Soil Quality to Mitigate Soil Degradation. Sustainability 7, 5875–5895.
163. Lambin, E.F., Gibbs, H.K., Ferreira, L., Grau, R., Mayaux, P., Meyfroidt, P., Morton, D.C., Rudel, T.K., Gasparri, I., Munger, J. (2013) Estimating the world's potentially available cropland using a bottom-up approach. Global Environmental Change, -.
164. Lambin, E.F., Meyfroidt, P. (2011) Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108, 3465–3472.
165. Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., Bald, A.B., Bertollini, R., Bose-OReilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potonik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M. (2018) The Lancet Commission on pollution and health. The Lancet 391, 462–512.
166. Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J. (2014) 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Research Letters 9, 105011.
167. Law, E.A., Wilson, K.A. (2015) Providing Context for the Land-Sharing and Land-Sparing Debate. Conservation Letters 8, 404–413.
168. Leclère, D., Havlík, P., Fuss, S., Schmid, E., Mosnier, A., Walsh, B., Valin, H., Herrero, M., Khabarov, N., Obersteiner, M. (2014) Climate change induced transformations of agricultural systems: insights from a global model. Environmental Research Letters 9, 1748–9326.
169. Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., Palma, A.D., DeClerck, F.A.J., Marco, M.D., Doelman, J.C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J.P., Hill, S.L.L., Humpenöder, F., Jennings, N., Krisztin, T., Mace, G.M., Ohashi, H., Popp, A., Purvis, A., Schipper, A.M., Tabeau, A., Valin, H., van Meijl, H., van Zeist, W.-J., Visconti, P., Alkemade, R., Almond, R., Bunting, G., Burgess, N.D., Cornell, S.E., Fulvio, F.D., Ferrier, S., Fritz, S., Fujimori, S., Grooten, M., Harwood, T., Havlik, P., Herrero, M., Hoskins, A.J., Jung, M., Kram, T., Lotze-Campen, H., Matsui, T., Meyer, C., Nel, D., Newbold, T., Schmidt-Traub, G., Stehfest, E., Strassburg, B.B.N., van Vuuren, D.P., Ware, C., Watson, J.E.M., Wu, W., Young, L. (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585, 551–556.
170. Licker, R., Johnston, M., Foley, J.A., Barford, C.C., Kucharik, C.J., Monfreda, C., Ramankutty, N. (2010) Mind the gap: how do climate and agricultural management explain the `yield gap' of croplands around the world? Global Ecology and Biogeography 19, 769–782.
171. Liu, J., Hertel, T.W., Lammers, R.B., Prusevich, A., Baldos, U.L.C., Grogan, D.S., Frolking, S. (2017) Achieving sustainable irrigation water withdrawals: global impacts on food security and land use. Environmental Research Letters 12, 104009.
172. Lloyd, S.J., Bangalore, M., Chalabi, Z., Kovats, R.S., Hallegatte, S., Rozenberg, J., Valin, H., Havlik, P. (2018) A Global-Level Model of the Potential Impacts of Climate Change on Child Stunting via Income and Food Price in 2030. Environmental Health Perspectives 126, 097007.
173. Lobell, D.B., Baldos, U.L.C., Hertel, T.W. (2013) Climate adaptation as mitigation: the case of agricultural investments. Environmental Research Letters 8, 015012.

174. Lotze-Campen, H., Lucht, W., Müller, C., Bondeau, A., Smith, P. (2005) How tight are the limits to land and water use? - Combined impacts of food demand and climate change. Advances in Geosciences 4, 23–28.
175. Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., Lucht, W. (2008) Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agricultural Economics 39, 325–338.
176. Lotze-Campen, H., von Lampe, M., Kyle, P., Fujimori, S., Havlik, P., van Meijl, H., Hasegawa, T., Popp, A., Schmitz, C., Tabeau, A., Valin, H., Willenbockel, D., Wise, M. (2014) Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. Agricultural Economics 45, 103–116.
177. Ludena, C.E., Hertel, T.W., Preckel, P.V., Foster, K., Nin, A. (2007) Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. Agricultural Economics 37, 1–17.
178. Lun, F., Liu, J., Ciais, P., Nesme, T., Chang, J., Wang, R., Goll, D., Sardans, J., Peuelas, J., Obersteiner, M. (2018) Global and regional phosphorus budgets in agricultural systems and their implications for phosphorus-use efficiency. Earth System Science Data 10, 1–18.
179. MacDonald, G.K., Bennett, E.M., Potter, P.A., Ramankutty, N. (2011) Agronomic phosphorus imbalances across the world}s croplands. Proceedings of the National Academy of Sciences 108, 3086–3091.
180. Malthus, T. (1798) An Essay on the Principle of Population. J. Johnson.
181. Matson, P.A. (1997) Agricultural Intensification and Ecosystem Properties. Science 277, 504–509.
182. Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E.M. (2016) Biodiversity: The ravages of guns, nets and bulldozers. Nature 536, 143–145.
183. Mbow, C., Rosenzweig, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M.-G., Sapkota, T., others, (2019) Food Security, Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, 437–550.
184. Meadows, D.H., Meadows, D.L., Randers, J., Behrens, I., William W. (1972) The limits to growth. A report for the Club of Rome’s project on the predicament of mankind. Universe Books.
185. Mehrabi, Z., Ellis, E.C., Ramankutty, N. (2018) The challenge of feeding the world while conserving half the planet. Nature Sustainability 1, 409–412.
186. Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being : Scenarios, Volume 2. Island Press.
187. Mogollon, J.M., Beusen, A.H.W., van Grinsven, H.J.M., Westhoek, H., Bouwman, A.F. (2018a) Future agricultural phosphorus demand according to the shared socioeconomic pathways. Global Environmental Change 50, 149–163.
188. Mogollon, J.M., Lassaletta, L., Beusen, A.H.W., van Grinsven, H.J.M., Westhoek, H., Bouwman, A.F. (2018b) Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways. Environmental Research Letters 13, 044008.
189. Möhring, N., Ingold, K., Kudsk, P., Martin-Laurent, F., Niggli, U., Siegrist, M., Studer, B., Walter, A., Finger, R. (2020) Pathways for advancing pesticide policies. Nature Food 1, 535–540.
190. Morse, S.S., Mazet, J.A.K., Woolhouse, M., Parrish, C.R., Carroll, D., Karesh, W.B., Zambrana-Torrelio, C., Lipkin, W.I., Daszak, P. (2012) Prediction and prevention of the next pandemic zoonosis. The Lancet 380, 1956–1965.
191. Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A. (2012) Closing yield gaps through nutrient and water management. Nature 490, 254–257.
192. Mueller, N.D., West, P.C., Gerber, J.S., MacDonald, G.K., Polasky, S., Foley, J.A. (2014) A tradeoff frontier for global nitrogen use and cereal production. Environmental Research Letters 9, 054002.
193. Müller, B., Hoffmann, F., Heckelei, T., Müller, C., Hertel, T.W., Polhill, J.G., van Wijk, M., Achterbosch, T., Alexander, P., Brown, C., Kreuer, D., Ewert, F., Ge, J., Millington, J.D.A., Seppelt, R., Verburg, P.H., Webber, H. (2020) Modelling food security: Bridging the gap between the micro and the macro scale. Global Environmental Change 63, 102085.
194. Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D., Bloom, A.J., Carlisle, E., Dietterich, L.H., Fitzgerald, G., Hasegawa, T., others (2014) Increasing CO2 threatens human nutrition. Nature 510, 139–142.
195. Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T.B., Mason-D’Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R., Rosegrant, M. (2018) Income growth and climate change effects on global nutrition security to mid-century. Nature Sustainability 1, 773–781.

196. Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., von Lampe, M., Lotze-Campen, H., Mason D'Croz, D., van Meijl, H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A., Willenbockel, D. (2014) Climate change effects on agriculture: Economic responses to biophysical shocks. Proceedings of the National Academy of Sciences 111, 3274–3279.
197. Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., Palma, A.D., Ferrier, S., Hill, S.L.L., Hoskins, A.J., Lysenko, I., Phillips, H.R.P., Burton, V.J., Chng, C.W.T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B.I., Whitmee, S., Zhang, H., Scharlemann, J.P.W., Purvis, A. (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353, 288–291.
198. Newbold, T., Hudson, L.N., Hill, S.L.L., Contu, S., Lysenko, I., Senior, R.A., Börger, L., Bennett, D.J., Choimes, A., Collen, B., Day, J., Palma, A.D., D\'\i, az, Sandra, Echeverria-Londo\~n, o, Susy, Edgar, M.J., Feldman, A., Garon, M., Harrison, M.L.K., Alhusseini, T., Ingram, D.J., Itescu, Y., Kattge, J., Kemp, V., Kirkpatrick, L., Kleyer, M., Correia, D.L.P., Martin, C.D., Meiri, S., Novosolov, M., Pan, Y., Phillips, H.R.P., Purves, D.W., Robinson, A., Simpson, J., Tuck, S.L., Weiher, E., White, H.J., Ewers, R.M., Mace, G.M., Scharlemann, J.P.W., Purvis, A. (2015) Global effects of land use on local terrestrial biodiversity. Nature 520, 45–50.
199. Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P., Hens, L. (2016) Chemical Pesticides and Human Health: The Urgent Need for a New Concept in Agriculture. Frontiers in Public Health 4.
200. Nkonya, E., Mirzabaev, A., Von Braun, J. (2016) Economics of land degradation and improvement--A global assessment for sustainable development. Springer Nature.
201. Nougadère, A., Sirot, V., Kadar, A., Fastier, A., Truchot, E., Vergnet, C., Hommet, F., Bayl, J., Gros, P., Leblanc, J.-C. (2012) Total diet study on pesticide residues in France: Levels in food as consumed and chronic dietary risk to consumers. Environment International 45, 135–150.
202. O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B.L., Riahi, K., Sillmann, J., van Ruijven, B.J., van Vuuren, D., Carlisle, D., Conde, C., Fuglestvedt, J., Green, C., Hasegawa, T., Leininger, J., Monteith, S., Pichs-Madruga, R. (2020) Achievements and needs for the climate change scenario framework. Nature Climate Change 10, 1074–1084.
203. O'Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., Mathur, R., Vuuren, D. (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122, 387–400.
204. Obersteiner, M., Walsh, B., Frank, S., Havlik, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S., van Vuuren, D. (2016) Assessing the land resource-food price nexus of the Sustainable Development Goals. Science Advances 2, e1501499–e1501499.
205. OECD (2012) OECD Environmental Outlook to 2050. OECD Publishing.
206. OECD (2016) Alternative Futures for Global Food and Agriculture. OECD Publishing, Paris.
207. OECD, (2019) The Heavy Burden of Obesity: The Economics of Prevention. OECD Publishing.
208. OECD, IIASA (2020) Systemic Thinking for Policy Making: The Potential of Systems Analysis for Addressing Global Policy Challenges in the 21st Century. OECD.
209. Palazzo, A., Valin, H., Batka, M., Havlik, P., (2019) Investment needs for irrigation infrastructure along different socio-economic pathways. World Bank, Washington DC.
210. Parodi, A., Leip, A., Boer, I.J.M.D., Slegers, P.M., Ziegler, F., Temme, E.H.M., Herrero, M., Tuomisto, H., Valin, H., Middelaar, C.E.V., Loon, J.J.A.V., Zanten, H.H.E.V. (2018) The potential of future foods for sustainable and healthy diets. Nature Sustainability 1, 782–789.
211. Parson, E.A., Fisher-Vanden, K. (1997) Integrated Assessment Models of Global Climate Change. Annual Review of Energy and the Environment 22, 589–628.
212. Pastor, A.V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P., Ludwig, F. (2019) The global nexus of food}trade}water sustaining environmental flows by 2050. Nature Sustainability.
213. Patz, J.A., Daszak, P., Tabor, G.M., Aguirre, A.A., Pearl, M., Epstein, J., Wolfe, N.D., Kilpatrick, A.M., Foufopoulos, J., Molyneux, D., Bradley, D.J. (2004) Unhealthy Landscapes: Policy Recommendations on Land Use Change and Infectious Disease Emergence. Environmental Health Perspectives 112, 1092–1098.
214. Persson, U.M. (2015) The impact of biofuel demand on agricultural commodity prices: a systematic review. Wiley Interdisciplinary Reviews: Energy and Environment 4, 410–428.
215. Phalan, B., Green, R.E., Dicks, L.V., Dotta, G., Feniuk, C., Lamb, A., Strassburg, B.B.N., Williams, D.R., z. Ermgassen, E.K.H.J., Balmford, A. (2016)

How can higher-yield farming help to spare nature? Science 351, 450–451.
216. Phalan, B., Onial, M., Balmford, A., Green, R.E. (2011) Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333, 1289–1291.
217. Pikaar, I., Matassa, S., Bodirsky, B.L., Weindl, I., Humpenoder, F., Rabaey, K., Boon, N., Bruschi, M., Yuan, Z., van Zanten, H., others (2018) Decoupling livestock from land use through industrial feed production pathways. Environmental Science \& Technology 52, 7351–7359.
218. Popp, A., Calvin, K., Fujimori, S., Havlík, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., van Vuuren, D.P. (2017) Land-use futures in the shared socio-economic pathways. Global Environmental Change 42, 331–345.
219. Popp, A., Lotze-Campen, H., Bodirsky, B. (2010) Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Global Environmental Change 20, 451–462.
220. Pradhan, P., Costa, L., Rybski, D., Lucht, W., Kropp, J.P. (2017) A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earth{\textquotesingle}s Future 5, 1169–1179.
221. Pravalie, R., Patriche, C., Borrelli, P., Panagos, P., Ro?ca, B., Dumitracu, M., Nita, I.-A., Svulescu, I., Birsan, M.-V., Bandoc, G. (2021) Arable lands under the pressure of multiple land degradation processes. A global perspective. Environmental Research 194, 110697.
222. Ranganathan, J., Vennard, D., Waite, R., Dumas, P., Lipinski, B., Searchinger, T.I.M., Authors, G.-W.M., (2016) Shifting diets for a sustainable food future. World Resources Institute, 831878447–1548317259.
223. Roberts, C.M., Hawkins, J.P., Gell, F.R. (2005) The role of marine reserves in achieving sustainable fisheries. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 123–132.
224. Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A. (2009) A safe operating space for humanity. Nature 461, 472–475.
225. Rosegrant, M.W., Sulser, T.B., Mason-D'Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., Zhu, T., Ringler, C., Wiebe, K.D., Robinson, S., others (2017) Quantitative foresight modeling to inform the CGIAR research portfolio. International Food Policy Research Institute.
226. Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W. (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences 111, 3268–3273.
227. Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., Antle, J.M., Nelson, G.C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., Winter, J.M. (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agricultural and Forest Meteorology 170, 166–182.
228. Ruel, M.T., Alderman, H. (2013) Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? The Lancet 382, 536–551.
229. Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., Rockström, J. (2019) Six Transformations to achieve the Sustainable Development Goals. Nature Sustainability 2, 805–814.
230. Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., Morgan, L.E., Mouillot, D., Palacios-Abrantes, J., Possingham, H.P., Rechberger, K.D., Worm, B., Lubchenco, J. (2021) Protecting the global ocean for biodiversity, food and climate. Nature 592, 397–402.
231. Sala, O.E. (2000) Global Biodiversity Scenarios for the Year 2100 $$. Science 287, 1770–1774.
232. Sattari, S.Z., Bouwman, A.F., Giller, K.E., van Ittersum, M.K. (2012) Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proceedings of the National Academy of Sciences 109, 6348-6353.
233. Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Coln-Gonzlez, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh,

Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P. (2013) Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences 111, 3245–3250.
234. Schleicher, J., Zaehringer, J.G., Fastre, C., Vira, B., Visconti, P., Sandbrook, C. (2019) Protecting half of the planet could directly affect over one billion people. Nature Sustainability.
235. Schmidt-Traub, G., Obersteiner, M., Mosnier, A. (2019) Fix the broken food system in three steps. Nature 569, 181–183.
236. Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Krause, M., Weindl, I. (2012) Trading more food: Implications for land use, greenhouse gas emissions, and the food system. Global Environmental Change 22, 189–209.
237. Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlík, P., Heyhoe, E., D'Croz, D.M., Popp, A., Sands, R.D., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H. (2014) Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. Agricultural Economics 45, 69–84.
238. Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., von Gunten, U., Wehrli, B. (2010) Global Water Pollution and Human Health. Annual Review of Environment and Resources 35, 109–136.
239. Searchinger, T., Edwards, R., Mulligan, D., Heimlich, R., Plevin, R. (2015) Do biofuel policies seek to cut emissions by cutting food? Science 347, 1420–1422.
240. Seppelt, R., Arndt, C., Beckmann, M., Martin, E.A., Hertel, T.W. (2020) Deciphering the Biodiversity}Production Mutualism in the Global Food Security Debate. Trends in Ecology {\&} Evolution 35, 1011–1020.
241. Sinha, E., Michalak, A.M., Calvin, K.V., Lawrence, P.J. (2019) Societal decisions about climate mitigation will have dramatic impacts on eutrophication in the 21st century. Nature Communications 10.
242. Sloat, L.L., Davis, S.J., Gerber, J.S., Moore, F.C., Ray, D.K., West, P.C., Mueller, N.D. (2020) Climate adaptation by crop migration. Nature Communications 11.
243. Smith, L.C., Haddad, L.J. (2000) Explaining child malnutrition in developing countries: A cross-country analysis. International Food Policy Research International Food Policy Research Institute.
244. Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Hoang, A.L., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M.A., Manning, F.C., Nampanzira, D., Arias-Navarro, C., Vizzarri, M., House, J., Roe, S., Cowie, A., Rounsevell, M., Arneth, A. (2019) Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology 26, 1532–1575.
245. Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C. (2015) Biophysical and economic limits to negative CO2 emissions. Nature Climate Change 6, 42–50.
246. Smith, P., Gregory, P.J., van Vuuren, D.P., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J. (2010) Competition for land. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2941–2957.
247. Smith, P., Haberl, H., Popp, A., Erb, K.-h., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S. (2013) How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biology 19, 2285–2302.
248. Smith, V.H., Glauber, J.W. (2019) Trade, policy, and food security. Agricultural Economics 51, 159–171.
249. Soergel, B., Kriegler, E., Bodirsky, B.L., Bauer, N., Leimbach, M., Popp, A. (2021) Combining Ambitious Climate Policies with Efforts to Eradicate Poverty. Nature Communications.
250. Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W. (2018a) Options for keeping the food system within environmental limits. Nature.
251. Springmann, M., Godfray, H.C.J., Rayner, M., Scarborough, P. (2016a) Analysis and valuation

of the health and climate change cobenefits of dietary change. Proceedings of the National Academy of Sciences 113, 4146–4151.
252. Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H.C.J., Gollin, D., Rayner, M., Ballon, P., Scarborough, P. (2016b) Global and regional health effects of future food production under climate change: a modelling study. The Lancet 387, 1937–1946.
253. Springmann, M., Wiebe, K., Mason-D\textquotesingle, C., Daniel, Sulser, T.B., Rayner, M., Scarborough, P. (2018b) Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. The Lancet Planetary Health 2, e451–e461.
254. Srinivasan, U.T., Cheung, W.W.L., Watson, R., Sumaila, U.R. (2010) Food security implications of global marine catch losses due to overfishing. Journal of Bioeconomics 12, 183–200.
255. Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S. (2015) Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855–1259855.
256. Stehfest, E., Bouwman, A.F., van Vuuren, D.P., den Elzen, M., Eickhout, B., Kabat, P. (2009) Climate benefits of changing diet. Climatic Change 95, 83–102.
257. Stehfest, E., van den Berg, M., Woltjer, G., Msangi, S., Westhoek, H. (2013) Options to reduce the environmental effects of livestock production – Comparison of two economic models. Agricultural Systems 114, 38–53.
258. Stehfest, E., van Zeist, W.-J., Valin, H., Havlik, P., Popp, A., Kyle, P., Tabeau, A., Mason-D'Croz, D., Hasegawa, T., Bodirsky, B.L., Calvin, K., Doelman, J.C., Fujimori, S., Humpenöder, F., Lotze-Campen, H., van Meijl, H., Wiebe, K. (2019) Key determinants of global land-use projections. Nature Communications 10.
259. Steiner, A., Aguilar, G., Bomba, K., Bonilla, J.P., Campbell, A., Echeverria, R., Gandhi, R., Hedegaard, C., Holdorf, D., Ishii, N., Quinn, K., Ruter, B., Sunga, I., Sukhdev, P., Verghese, S., Voegele, J., Winters, P., Campbell, B., Dinesh, D., Huyer, S., Jarvis, A., Loboguerrero Rodriguez, A.M., Millan, A., Thornton, P., Wollenberg, L., Zebiak, S., (2020) Actions to transform food systems under climate change. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
260. Steinfeld, H., Gerber, P.J., Wassenaar, T.D., Castel, V., de Haan, C. (2006) Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations.
261. Stokstad, E. (2014) Ammonia Pollution From Farming May Exact Hefty Health Costs. Science 343, 238–238.
262. Strzepek, K., Boehlert, B. (2010) Competition for water for the food system. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2927–2940.
263. Swinburn, B.A., Sacks, G., Hall, K.D., McPherson, K., Finegood, D.T., Moodie, M.L., Gortmaker, S.L. (2011) The global obesity pandemic: shaped by global drivers and local environments. The Lancet 378, 804–814.
264. Swinnen, J., McDermott, J. (2020) COVID-19 and global food security. International Food Policy Research Institute (IFPRI).
265. Swinnen, J., Squicciarini, P. (2012) Mixed Messages on Prices and Food Security. Science 335, 405–406.
266. Tabeau, A., van Meijl, H., Overmars, K.P., Stehfest, E. (2017) REDD policy impacts on the agri-food sector and food security. Food Policy 66, 73–87.
267. Tilman, D., Balzer, C., Hill, J., Befort, B.L. (2011) Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108, 20260–20264.
268. Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S. (2002) Agricultural sustainability and intensive production practices. Nature 418, 671–677.
269. Tilman, D., Clark, M. (2014) Global diets link environmental sustainability and human health. Nature 515, 518–522.
270. Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D. (2001) Forecasting Agriculturally Driven Global Environmental Change. Science 292, 281–284.
271. Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R. (2009) Beneficial Biofuels--The Food, Energy, and Environment Trilemma. Science 325, 270–271.
272. Tongeren, F., Meijl, H., Surry, Y. (2001) Global models applied to agricultural and trade policies: a review and assessment. Agricultural Economics 26, 149–172.
273. UN (1996) Rome Declaration on World Food Security United Nations.
274. UN (2015) Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.

275. Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E., Obersteiner, M. (2013) Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? Environmental Research Letters 8, 035019.
276. Valin, H., Sands, R.D., van der Mensbrugghe, D., Nelson, G.C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Manson-D'Croz, D., Paltsev, S., Rolinski, S., Tabeau, A., van Meijl, H., von Lampe, M., Willenbockel, D. (2014) The Future of Food Demand: Understanding Differences in Global Economic Models. Agricultural Economics 45, 51–67.
277. van den Bos Verma, M., de Vreede, L., Achterbosch, T., Rutten, M.M. (2020) Consumers discard a lot more food than widely believed: Estimates of global food~waste using an energy gap approach and~affluence elasticity of food waste. {PLOS} {ONE} 15, e0228369.
278. van der Esch, S., ten Brink, B., Stehfest, E., Bakkenes, M., Sewell, A., Bouwman, A., Meijer, J., Westhoek, H., van den Berg, M., van den Born, G.J., others (2017) Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: scenarios for the UNCCD Global Land Outlook.
279. van der Velde, M., See, L., You, L., Balkovic, J., Juraj, Fritz, S., Khabarov, N., Obersteiner, M., Wood, S. (2013) Affordable Nutrient Solutions for Improved Food Security as Evidenced by Crop Trials. PLoS ONE 8, e60075.
280. van Dijk, M., Morley, T., Rau, M.L., Saghai, Y. (2021) Systematic review and meta-analysis of global food security projections to 2050. Nature Food (in press).
281. van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. (2013) Yield gap analysis with local to global relevance—A review. Field Crops Research 143, 4–17.
282. van Meijl, H., Shutes, L., Valin, H., Stehfest, E., van Dijk, M., Kuiper, M., Tabeau, A., van Zeist, W.-J., Hasegawa, T., Havlik, P. (2020a) Modelling alternative futures of global food security: Insights from FOODSECURE. Global Food Security 25, 100358.
283. van Meijl, H., Tabeau, A., Stehfest, E., Doelman, J., Lucas, P. (2020b) How food secure are the green, rocky and middle roads: food security effects in different world development paths. Environmental Research Communications 2, 031002.
284. van Vliet, J., Eitelberg, D.A., Verburg, P.H. (2017) A global analysis of land take in cropland areas and production displacement from urbanization. Global Environmental Change 43, 107–115.
285. van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W. (2010) Phosphorus demand for the 1970}2100 period: A scenario analysis of resource depletion. Global Environmental Change 20, 428–439.
286. van Vuuren, D.P., Bouwman, L.F., Smith, S.J., Dentener, F. (2011a) Global projections for anthropogenic reactive nitrogen emissions to the atmosphere: an assessment of scenarios in the scientific literature. Current Opinion in Environmental Sustainability 3, 359–369.
287. van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S.K. (2011b) The representative concentration pathways: an overview. Climatic Change 109, 5–31.
288. van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Weyant, J. (2011c) A special issue on the RCPs. Climatic Change 109, 1–4.
289. van Vuuren, D.P., Kok, M., Lucas, P.L., Prins, A.G., Alkemade, R., van den Berg, M., Bouwman, L., van der Esch, S., Jeuken, M., Kram, T., Stehfest, E. (2015) Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. Technological Forecasting and Social Change 98, 303–323.
290. van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., van Sluisveld, M.A.E. (2018) Alternative pathways to the 1.50.167em}C target reduce the need for negative emission technologies. Nature Climate Change 8, 391–397.
291. van Wijk, M.T. (2014) From global economic modelling to household level analyses of food security and sustainability: How big is the gap and can we bridge it? Food Policy 49, 378–388.
292. van Wijk, M.T., Rufino, M.C., Enahoro, D., Parsons, D., Silvestri, S., Valdivia, R.O., Herrero, M. (2014) Farm household models to analyse food security in a changing climate: A review. Global Food Security 3, 77–84.
293. van Zanten, H.H.E., Mollenhorst, H., Oonincx, D.G.A.B., Bikker, P., Meerburg, B.G., de Boer, I.J.M. (2015) From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. Journal of Cleaner Production 102, 362–369.
294. van Zeist, W.-J., Stehfest, E., Doelman, J.C., Valin, H., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Humpenöder, F., Kyle, P., Lotze-Campen, H., Mason-D\textquotesingle, C., Daniel, van Meijl, H., Popp, A., Sulser, T.B., Tabeau, A., Verhagen, W., Wiebe, K. (2020) Are scenario projections

overly optimistic about future yield progress? Global Environmental Change 64, 102120.
295. Villoria, N.B., Byerlee, D., Stevenson, J., (2013) The Effects of Agricultural Technological Progress on Deforestation: What do we really know? Purdue University.
296. von Braun, J., Zamagni, S., Sorondo, M.S. (2020) The moment to see the poor. Science 368, 214–214.
297. von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason D.'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H. (2014) Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agricultural Economics 45, 3–20.
298. Wada, Y., Bierkens, M.F.P. (2014) Sustainability of global water use: past reconstruction and future projections. Environmental Research Letters 9, 104003.
299. Waite, R., Beveridge, M., Brummett, R., Castine, S., Chaiyawannakarn, N., Kaushik, S., Mungkung, R., Nawapakpilai, S., Phillips, M., (2014) Improving productivity and environmental performance of aquaculture. World Resources Institute.
300. Walsh, B.J., Rydzak, F., Palazzo, A., Kraxner, F., Herrero, M., Schenk, P.M., Ciais, P., Janssens, I.A., Peuelas, J., Niederl-Schmidinger, A., Obersteiner, M. (2015) New feed sources key to ambitious climate targets. Carbon Balance and Management 10.
301. Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J. (2013) The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. Proceedings of the National Academy of Sciences.
302. Weindl, I., Lotze-Campen, H., Popp, A., Müller, C., Havlík, P., Herrero, M., Schmitz, C., Rolinski, S. (2015) Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environmental Research Letters 10, 094021.
303. Wheeler, T., von Braun, J. (2013) Climate Change Impacts on Global Food Security. Science 341, 508–513.
304. Wicke, B., van der Hilst, F., Daioglou, V., Banse, M., Beringer, T., Gerssen-Gondelach, S., Heijnen, S., Karssenberg, D., Laborde, D., Lippe, M., van Meijl, H., Nassar, A.M., Powell, J., Prins, A.G., Rose, S.K., Smeets, E.M.W., Stehfest, E., Tyner, W.E., Verstegen, J.A., Valin, H., van Vuuren, D.P., Yeh, S., Faaij, A.P.C. (2014) Model collaboration for the improved assessment of biomass supply, demand and impacts. GCB Bioenergy in press.
305. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., Vries, W.D., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S., Murray, C.J.L. (2019) Food in the Anthropocene: the EAT}Lancet Commission on healthy diets from sustainable food systems. The Lancet 393, 447–492.
306. Wilson, E.O. (2016) Half-earth: our planet's fight for life. WW Norton \& Company.
307. Wirsenius, S., Azar, C., Berndes, G. (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems 103, 621–638.
308. Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S., Campbell, B.M. (2016) Reducing emissions from agriculture to meet the 2 °C target. Global Change Biology, n/a-n/a.
309. Yu, W., Hertel, T.W., Preckel, P., Eales, J. (2004) Projecting World Food Demand Using Alternative Demand Systems. Economic Modelling 21, 99–129.
310. Zabel, F., Putzenlechner, B., Mauser, W. (2014) Global Agricultural Land Resources: A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions. {PLOS} {ONE} 9, e107522.
311. Zhang, J., Beusen, A.H.W., Apeldoorn, D.F.V., Mogollon, J.M., Yu, C., Bouwman, A.F. (2017) Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century. Biogeosciences 14, 2055–2068.
312. Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y. (2015) Managing nitrogen for sustainable development. Nature.
313. Zurek, M., Hebinck, A., Selomane, O. (2021) Looking across diverse food system futures: Implications for climate change and the environment. Q Open 1.

7. APPENDIX. SUSTAINABLE DEVELOPMENT GOAL 2

The Agenda 2030 for Sustainable Development (UN, 2015) defines SDG2 as follows:

Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture

- **Target 2.1.** By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round
- **Target 2.2.** By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons
- **Target 2.3.** By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment
- **Target 2.4.** By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality
- **Target 2.5.** By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed
- **Target 2.a.** Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks to enhance agricultural productive capacity in developing countries, in particular least developed countries
- **Target 2.b.** Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round
- **Target 2.c.** Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility

This Report was prepared by members of the Scientific Group and members of its Research Partners.

UNITED NATIONS
FOOD SYSTEMS
SUMMIT 2021
The Scientific Group for the
UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

FRUITS AND VEGETABLES FOR HEALTHY DIETS: PRIORITIES FOR FOOD SYSTEM RESEARCH AND ACTION

by Jody Harris, Bart de Steenhuijsen Piters, Stepha McMullin,
Babar Bajwa, Ilse de Jager and Inge D. Brouwer

ABSTRACT

Fruits and vegetables are vital for healthy diets, but intake remains low for a majority of the global population. This paper reviews academic literature on food system issues, and opportunities for research and action, as an input into the 2021 UN Food Systems Summit in the context of the International Year of Fruits and Vegetables.

The paper summarises evidence underpinning food system actions to make fruits and vegetables more available, accessible and desirable through push (production and supply), pull (demand and activism) and

ABOUT THE AUTHORS

Jody Harris, World Vegetable Center

Bart de Steenhuijsen Piters, Wageningen Economic Research

Stepha McMullin, World Agroforestry, a partnership of CIFOR-ICRAF, and CGIAR FTA

Bajwa Babar, CABI

Ilse de Jager, Wageningen University and Research

Inge D. Brouwer, Wageningen University and Research, and CGIAR-A4NH

policy (legislation and governance) mechanisms, with action options at macro (global and national) meso (institutional, city and community) and micro (household and individual) levels. It also suggests the need to recognise and address power disparities across food systems, and trade-offs among diet, livelihood and environmental food system outcomes.

We conclude that there is still a need to better understand the different ways that food systems can make fruits and vegetables available, affordable, accessible and desirable across places and over time, but that we know enough to accelerate action in support of fruit- and vegetable-rich food systems driving healthy diets for all.

WHY FRUITS AND VEGETABLES? WHY NOW?

Fruits and vegetables are vital for healthy diets, with broad consensus that a diverse diet containing a range of plant foods (and their associated nutrients, phytonutrients and fibre) is needed for health and wellbeing[1]. Studies have suggested intake ranges of 300-600g per day (200-600g of vegetables and 100-300g of fruits) to meet different combinations of health and environmental goals[2-4]. The World Health Organisation (WHO) recommends adults to eat at least 400g of fruits and vegetables per day[5], with national food-based dietary guidelines translating these into recommendations to eat multiple portions of a variety of fruits and vegetables each day for health[6].

Despite this clear message, intake of fruits and vegetables remains low for a majority of the global population[4,7]. Low fruit and vegetable consumption is among the top-5 risk factors for poor health, with over 2 million deaths and 65 million Disability-Adjusted Life Years (DALYs) attributable to low intake of fruits, and 1.5 million deaths and 34 million DALYs attributable to low intake of vegetables globally each year, and particularly in low- and middle-income countries[4]. Low consumption is a global problem affecting high- and low-income countries: only 7% of countries in Africa, 7% in the Americas, and 11% in Europe reach 240 g/day of vegetables on average[7], and only 20% of individuals in low- and middle-income countries reach the recommendation of five servings of fruits and vegetables a day[8]. The mean global intake of vegetables is estimated to be around 190g/day and of fruits 81g/day. Studies generally agree that parts of Africa and the Pacific Islands have the lowest fruit and vegetable consumption, and East Asia has the highest vegetable (but not fruit) consumption[4, 7, 9].

Changes in fruit and vegetable consumption are happening against a backdrop of the 'nutrition transition' from traditional foods to processed and ultra-processed foods that are high in energy, fat , sugar and salt but poor in other essential nutrients[10]. This transition also brings opportunities to diversify into healthy diets containing more fresh fruits and vegetables, although for some populations there is less opportunity than for others11. Available literature does not suggest systematic differences in fruit and vegetable consumption between men and women in many contexts[8, 9], but it does highlight differences in consumption between rural and urban areas[12-14], and between populations with different levels of education and national income[8]. These differences illustrate that there is an equity issue across populations in accessing fruits and vegetables[15].

We now have good conceptual models for how food systems work to provide diets[16]. These help us to describe the structural and social constraints to fruit and vegetable consumption and research how these play out in different contexts and for different populations. Below, we summarise what we know (and what we need to know) about how to address the issues above through a set of push (production and supply), pull (demand and activism) and policy (legislation and governance) actions. We conclude that there is still a need to better understand the different ways that food systems can make fruits and vegetables available, accessible, affordable and desirable for all people, across places and over time, to meet global recommendations, but that we know enough to accelerate action in support of healthy diets. The year 2021 is the UN International Year of Fruits and Vegetables, embedded in the middle of the Decade of Action on Nutrition. Now is the time to prioritise understanding and addressing these issues to enable fruit- and vegetable-rich food systems driving healthy diets for all.

POLICY FACTORS: POLITICAL POWER

The Green Revolution in the latter part of the 20th century transformed agriculture's ability to produce sufficient calories to feed the world, but the focus on grain crops through funding, research, extension and technology development limited supply of nutrient-dense fruits and vegetables both through losses of wild sources with the promotion of monocultures, and through policy and structural impediments that crowded out non-staple crops[17]. Today, the combined international public research budget for maize, wheat, rice, and starchy tubers is 30 times than for vegetables for instance[18], and these incentives skew many of the technology and infrastructure drivers of food systems. This has fed into national food policies, which are normally focused on the production or import of staple crops (as a source of cheap calories) rather than diet quality through diversity of fresh foods (as a source of other essential nutrients)[19]. Following suit, food system data have focused largely on globally-tradable commodities, leading to a dearth of trustworthy and disaggregated data with which to track the production, price, trade or consumption of the diversity of fruits and vegetables[20] and global data are biased towards economically-relevant crops, often missing traditional fruits and vegetables and those produced non-commercially[21]. Research on food systems and diets often treats fruits and vegetables as a single food group, rather than looking at diversity within fruit and vegetable species, or amounts or variety consumed within the food group[22], further limiting our knowledge on the specifics of issues or actions.

At the same time, large structural changes outside of the food system, such as globalisation of supply chains and societies, and changing demographics and urbanisation, have shaped food regimes to prioritise foods that are non-perishable and globally tradable[23, 24], the very opposite of most fruits and vegetables whose perishability requires shorter food chains from farm to fork. Modern trade rules improve regulation on the safety of imported fruits and vegetables and may protect domestic production or improve supply of highly-traded commodities, but they also limit the ability of governments to protect public health policy space and institutional purchase of fresh foods[25] and tend to prioritise staple foods over fruits and vegetables while out-sourcing the environmental impacts of production to poor countries[1]. In many contexts, the concentration of inputs, distribution and retail of foods, including fruits and vegetables, in the hands of a few large companies has shifted food system choices away from the livelihood interests of producers, the health interests of consumers, and the environmental interests of all[26].

These broad and sweeping changes are not without interruption: the COVID-19 pandemic and previous economic shocks and natural disasters have disrupted many aspects of food systems and diets over time[27-29]. Such disruptions particularly affect fruits and vegetables because of their specific labour, storage and transport requirements[30] with at least temporary impacts of different shocks documented on the livelihoods of fruit and vegetable producers and on fruit and vegetable prices and consumption[28, 29, 31, 32]. These shocks have affected the diets and livelihoods of marginalised populations differently to those with economic or social power, further exacerbating inequity[33-35].

OPPORTUNITIES FOR RESEARCH AND ACTION

Each of these big-picture policy and political drivers has created food system 'lock-ins'[36] which have tended to steer away from pathways prioritising fruits and vegetables, and away from agronomic and food system paradigms – such as agroecology, a right to food, or food as a commons rather than a commodity[37-39] – that might promote a return to more diverse production systems. Policy decisions can start with evidence: we need to know more about how different production and distribution systems, based in different social and political traditions, drive the availability and accessibility of fruits and vegetables in food systems, and how they weather shocks to provide healthy diets sustainably and equitably. However, ultimately while data and evidence can reveal nuance in the issues and their solutions, food policy decisions are political (and ideally ethical) in reality, depending on priorities and tolerances of the actors involved in making those decisions[40]. Bringing together people with a stake in food systems to debate and decide policy, explicitly recognising disparities in power among them in contributing to outcome and decisions, is likely to lead to the most context-specific and equitable policy in practice when done well[41-43].

A starting point for addressing the lack of fruits and vegetables in food system policy is 'reverse thinking', putting the dietary outcomes we want from food systems up-front in responsive food policy-making and legislation, and working towards incentivising systems that create these[19]. A difficulty in achieving this vision is that different actor coalitions frame food system issues and priorities differently according to their interests and beliefs, so there is no single narrative to work towards[40, 44], and coherent diet and food system policy will require policy sectors to work together in non-traditional ways[45]. There is therefore a need to better understand how public and private decision-makers make food system choices and how other food system actors influence these, and implications for fruits and vegetables across food systems.

Public investment in agriculture is shown to impact the growth of production through the private sector, but different types of investment produce different results for different foods in different contexts[46], so we need to know more about how specific investments such as in breeding, production subsidies, and extension support play out in food environments for different fruits and vegetables. Acknowledging the imbalance of power between food system actors, illustrated by disparities between budgets of processed food producers[47] and public investment in healthy foods such as fruits and vegetables[18], is necessary in order to make transparent and health-positive policy, regulation and investment. Public policy shaping food environments – such as mandating vegetables in institutional meals (schools, workplaces, hospitals), setting incentives for healthy retail, and regulating food system actors[48-50] – is seen to improve intakes in some contexts. Similarly, land rights are a key issue for sustainable food access and production[51] and we need to know more about how these issues affect fruits and vegetables. For all of these analyses, better data and contextual knowledge on diverse fruits and vegetables in different systems is needed, particularly in low- and middle-income countries, to inform businesses, policy-makers, practitioners, workers and activists in making decisions within food systems.

PUSH FACTORS: PRODUCTION AND POST-HARVEST POWER

By the data we have, global fruit and vegetable production is insufficient to meet the WHO dietary recommendations and has been since global records began: in 1965, sufficient fruits and vegetables (≥400 g/day) were available for 17% of the global population, increasing to 55% in 201552. Supply varies widely between contexts: in Africa, only 13% of countries have an adequate aggregate vegetable supply while in Asia 61% do7. This is despite the fact that fruits and vegetables are valuable: the annual farmgate value of global fruit and vegetable production is nearly $1 trillion and exceeds the farmgate value of all food grains combined (US$ 837 billion)[53]. Most fruits and vegetables (about 92%) are not internationally traded, but the international trade in fruits and vegetables was still valued at US$ 138 billion in 2018.

Fruit and vegetable production needs to increase particularly in regions with low consumption, together with accompanying measures to prevent losses, to provide enough for healthy diets[52]. Scaling production is not straightforward, as fruits and vegetables have specific attributes – in terms of seasonal and agro-climatic differences, labour and input needs, knowledge and expertise, and storage and distribution – that mean there are particular trade-offs to consider. While we can in theory produce healthy diets within planetary boundaries[2], achieving national food-based dietary guidelines has been found to be incompatible with climate and environmental targets in a majority of 85 countries studied[54], and producing more fruits and vegetables may require more land, water and chemical inputs than producing staple foods in some contexts[55], with one-third of all greenhouse gas emissions produced by the food system[56]. Various studies show widespread misuse of agricultural chemicals, particularly on high-value vegetables, creating hazards for farm workers, consumers and the environment[57]. Foodborne diseases caused by biological contamination of food are also an important threat to public health particularly in low- and middle-income countries, and fruits and vegetables are among the riskiest foods for biological hazards[58].

Seed or planting stock is a key input into fruit and vegetable production, although it is a contested area: some see the introduction of (often proprietary) improved varieties of fruits and vegetables as necessary to transform the fruit and vegetable sector to one with increased volumes of regularly available quality products[53, 59-61]. Others stress the importance of local or cultural seed-saving and exchange of planting material for conserving farmer independence, agricultural diversity and food sovereignty[26, 62], and debates about the primacy of breeders' rights or farmers' rights are ongoing[63-65]. Beyond inputs, labour requirements in fruit and vegetable production are considerably higher than in cereal production, with labour costs making up more than 50% of production costs depending on the food grown, related to more skilled and intensive field operations[66, 67]. This is a positive for food system worker incomes, but extension services are often geared to staple crops, with little support for fruit and vegetable producers, limiting formal training opportunities68. Beyond the farm, post-farmgate midstream employment in developing regions constitutes roughly 20% of rural employment[69, 70]. It is assumed that many smallholders also engage in midstream fruit and vegetable chain operations, such as trade and processing, but fruit and vegetable value chains have not been a focus of this work so more knowledge is needed in this area.

Of food produced for human consumption, around one-third by volume or one-quarter by calories is either lost (before retail) or wasted (after purchase)[71]. Highly perishable fruits and vegetables have the highest rates of loss and waste, usually in the range of 40-50%[72, 73]. Local production is therefore central, and in many contexts ultra-local home-based fruit and vegetable production and wild plant gathering are important strategies[74, 75], as are 'under-utilised' species and many traditional fruits and vegetables that are often left out of data, policy and extension[76, 77]. Fruits and vegetables are particularly seasonal, which can be an advantage in diverse systems where different foods become available at different times, or a challenge where there are gluts and shortages leading to price change over the year[78, 79].

OPPORTUNITIES FOR RESEARCH AND ACTION

Clearly, more availability of a variety of fruits and vegetables is needed for everyone to meet recommendations. This can be achieved through increased production, although there are trade-offs between environmental sustainability and providing for diets: sustainable intensification using a wide range of approaches according to social, political and agro-ecological context to improve yields or protect against climate changes without environmental degradation has been suggested[53, 80] although further understanding of the implications of different approaches to fruit and vegetable production is needed. Organic agriculture meets goals on a range of environmental factors, including reduced chemical contamination of diets, but it has weaknesses in terms of lower productivity and reduced yield stability[81], and the subsidisation of chemical inputs makes it appear less profitable. Supporting the availability of planting material through formal (breeding and seed companies) and informal (seed-saving and sharing networks) channels is important[53].

The economic value of fruits and vegetables is a strong incentive for their production, but much of this value is captured by large global firms rather than smallholders, despite over 80% of fruit and vegetables being grown on smallholder family farms (< 20 hectares) in LMICs[67]. The smallholder nature of many fruit and vegetable producers and traders provides challenges and opportunities for vegetable supply[82], and the complexity of systems of traders and the heterogeneity of smallholders and their support needs (particularly peri-urban vegetable producers or women, who may not be engaged in formal extension systems[83, 84]) means that agricultural policy very often does not adequately support the twin goals of healthy food production and livelihood development[85]. Aggregation or contract farming are commonly used to reduce transaction costs and risk, and sell to modern channels such as supermarkets where demand for fruits and vegetables is growing[86, 87], although the impacts of commercialisation on the diets of commercial farmers themselves are mixed[88]. Farmer extension needs to be strengthened[53] and we need more documented understanding of how informal sectors and formal small- and medium enterprises involved in fruit and vegetable processing, distribution and retail can deliver more on desired food system outcomes. These need further research to understand how they play out in fruit and vegetable systems.

Better availability can also be achieved by addressing food loss and waste: in low-income countries through addressing on-farm pests and diseases, pre-maturity harvesting due to climate shocks or seasonal gluts, and inappropriate post-harvest handling, transport and storage, and in middle-/high-income countries addressing quality grading standards set by retailers[72]. Packaging of perishable fruits and vegetables can limit losses[89] but also contributes to environmental pollution and greenhouse gas emissions[56, 90]. More understanding is needed of the production, processing and distribution options and trade-offs, and of food loss and waste, specifically for fruits and vegetables in different contexts.

Physical availability of food varies depending on functioning supply chains, whether short or long. Food deserts and swamps associated with poorer diets occur where there is a lack of available fresh foods for local purchase, and exist particularly in poorer urban areas[91]. Physical access is a key driver of purchase (and by extension, consumption), with lack of fresh food outlets making consumption of fresh produce harder[92], and conversely living close to vegetable vendors making vegetable purchase more likely[93], suggesting that local access options are important in shaping diets.

PULL FACTORS: PEOPLE POWER

While availability of, and physical access to, sufficient fruits and vegetables is an important pre-requisite, there are other factors at the socio-economic and personal level that also impact their role in diets. Reviews of research suggest that in low-income countries similar determinants play a role in food choices as in high-income countries, at individual level (income, employment, education level, food knowledge, lifestyle, time), in the social environment (family and peer influence, cultural factors), and in the physical environment (food expenditure, lifestyle)[94].

Food prices interact with incomes to determine whether households can afford the components of a healthy diet, and fruits and vegetables, along with animal-source foods, are the most expensive element of a healthy diet by many metrics[95, 96] comprising around 40% of the cost of a healthy diet[97], although these costs tend to vary with season78. Fruits and vegetables are unaffordable for many, with 3 billion people unable to afford diverse healthy diets[97]. Fruits and vegetables appear more affordable when comparing prices per micronutrient, where they are likely to be a relatively low-cost source of varied vitamins, minerals, and phytonutrients[98], but this is not how most families choose their food.

Beyond a certain income level, affordability is not a driving factor for everyone everywhere: while an increase of fruit and vegetable consumption by income across geographical regions is confirmed in many studies, indicating that a low income is a barrier to fruit and vegetable consumption for some[8, 99], there is only a weak association between incomes and fruit and vegetable consumption, where on average (across 52 countries) 82% of the poorest quintile consume too few fruits and vegetables and 73% of the wealthiest quintile do[12]. As incomes rise, the consumption of meat, dairy and ultra-processed foods rise much faster than that of vegetables, and vegetable purchase in some contexts changes little across income groups, and hence vegetable consumption is relatively inelastic to income past a certain level[13], although fruits may be more consumed at higher incomes. With little change in consumption of vegetables across income groups in some contexts[100], affordability is not the largest driver of consumption for all.

Even if vegetables are available, accessible and affordable, most people still do not consume large enough quantities[12], particularly if they are not considered an acceptable or desirable food choice, for instance due to food safety or contamination concerns, taste preferences, or cultural appropriateness[101-103]. Low desirability of fruits and vegetables is particularly a problem among children and adolescents, with data across 73 countries showing that between 10-30% of students do not eat any vegetables at all in one-quarter of these countries[104].

OPPORTUNITIES FOR RESEARCH AND ACTION

Addressing affordability of fruits and vegetables is key to creating an environment where all can access a healthy diet, and affordability can come from a combination of lower retail prices (through productivity improvements, reduced post-harvest losses, or increased market efficiency for stable prices) and higher incomes (from inclusive economic growth and social safety nets)[105]. Cheap food is not necessarily good for healthy diets, fair livelihoods or biodiverse environments, so a focus on raising people up through fair wages is important[106]. Price subsidies of fruits and vegetables is a policy option that is popular with the public in some contexts[107], and there is evidence that price incentives to make fruits and vegetables more directly affordable have worked to increase consumption[108, 109]. These affordability interventions where fruits and vegetables are largely purchased can be combined with promoting home and community production or facilitation of foraging where the context allows[110-112].

Alongside ability to afford fruits and vegetables, the challenge is to enhance consumer choice of and preference for these foods. There is clear evidence that focusing on education at all levels is a key component for modifying behavioural changes in general[113], and nutrition literacy, social norms for healthy eating, and self-efficacy are key components of health-related behaviour change[114], although we know less for fruits and vegetables in particular. Nutrition literacy programmes generally target women, who are custodians of household nutrition in many contexts, but there may also be a need for community-targeted messages to change social norms[115]. Promoting traditional or under-utilised vegetables that are familiar was seen as a key policy option for healthy diets and environmental sustainability among an expert opinion Delphi panel[116], and the latest generation of food-based dietary guidelines start to move in this direction, but these efforts should better consider cultural acceptability and may require promotional efforts to increase the willingness of consumer to shift their tastes to new or forgotten foods[117]. Food composition data is lacking for many indigenous species, limiting the opportunity to develop appropriate nutritional messaging and promote wider use [118, 119].

Beyond appeals to public health, better understanding is required of consumers' preferences and behaviours with respect to these foods and what kinds of incentives might promote more consumption in different contexts. Strategic placement of fruit and vegetables in retail outlets is found to have a moderately significant effect on increasing fruit or vegetable servings[120], and early exposure to fruits and vegetables through schools may shape future preferences for healthier diets[121]. Marketing is a key factor shaping desirability, but is consistently applied for 'hedonic' (processed) rather than 'healthy' (nutrient-dense) foods[122]. On marketing issues, much is known about high-income countries[123] but less about low- and middle-income contexts where these approaches (understanding market segments and speaking to issues of desirability, aspiration, emotion and imagination) can be adapted for fruits and vegetables[124].

FRUIT AND VEGETABLE FOOD SYSTEMS: WHAT NEXT?

The brief review above has laid out evidence on the key food system issues for fruits and vegetables in healthy diets, and where available included evidence on actions to address these. From this summary, it is clear that we know on a broad scale the structural limitations to fruits and vegetables: global and national challenges of increasing production and accessing quality growing material shared equitably, local issues of ensuring affordability and addressing perishability and enabling everyone everywhere to access fruits and vegetables, and social issues of valuing vegetables for their role in cuisines and for health. It is also clear that the precise issues and solutions to these vary by food system context and by population, and that there are multiple potential routes towards solutions that sometimes clash on ideals. Food system actions to make fruits and vegetables more available, affordable, accessible and desirable through policy, push and pull mechanisms comprise various options working at macro (global and national) meso (institutional, city and community) and micro (household and individual) levels. Examples of actions from the review above are laid out in the table below.

It is unlikely that these are all of the options available to orient food systems towards fruit- and vegetable-rich diets, but these are the options that appear in the academic literature, albeit with varying levels of evidence. In addition, there are two important over-arching considerations when considering action options: 1) Acknowledging that power shapes food systems, from concentration of economic and political power in a few global agri-food businesses, through to marginalisation of certain groups in societies from accessing healthy diets, so this needs to be considered in terms of both inclusive processes in deciding policies and actions and in assessing their equity impacts[26, 125]. 2) There will be trade-offs among food system outcomes, so starting with a focus on healthy diets is important but understanding how food system decisions then impact fair livelihoods and sustainable environments is key[126]. We do not yet know enough to formulate clear actions to address these trade-offs, but they need to be acknowledged and openly debated by those taking food system decisions.

These actions are likely to be foundational to creating food systems change towards enabling fruit- and vegetable-rich diets. Each of these actions will not change diets when implemented alone, but rather packages of actions need to address particular limitations to fruit and vegetable consumption. These need to be considered in context, in light of an understanding of food system issues and bottlenecks limiting healthy diets in different places and for different people. It is likely that the best way to start is to bring together diverse groups of people interested in these issues at the different levels, to understand the issues and options from different perspectives and together prioritise which actions should be undertaken first in their own context. This is not easy, given inherent power disparities among interested parties, but with care and inclusion a strategy, policy or plan can be made to move towards enabling fruit and vegetable-rich food systems.

To guide better action, we need more evidence and understanding. We know a lot about a small fraction of the fruit and vegetable species of which we are aware, and very little about the rest. We know that there are disparities in diets in different contexts, but less how to address the political, social and equity determinants of who gets to eat fruits and vegetables. We know much about the technical production and market aspects of fruits and vegetables, but less about bottlenecks in bringing these to low- and middle-income countries, and we do not know enough about how these things

Table 1 Examples of pull, push and policy actions at different levels

	Macro (global and national)	Meso (institutional, city and community)	Micro (household and individual)
Policy	– R&D investment – Right to food legislation – Food safety regulation	– Zoning and marketing regulation – Prioritising fruit and vegetables (F&V) in institutional food procurement plans	– Protected foraging rights – Land rights
Push	– Production subsidies – Efficiency through breeding and technology – Support to diverse alternative production paradigms – Infrastructure development – Fair finance access	– Quality F&V planting material (formal and informal systems) – Pre- and post-harvest practices and packaging – Improving market access, shortening food supply chains – F&V extension and training – Support to fresh food outlets	– Home & community gardens
Pull	– Price subsidies – Social safety nets – Food-based dietary guidelines	– F&V-rich institutional meals – Basic processing for preservation – Social marketing campaigns – Promotion of traditional F&V – F&V product placement in shops and canteens	– Nutrition literacy campaigns – School gardens and learning for shaping preferences

change with context or over time. Work drawing on different academic traditions, including valuing traditional and tacit knowledge, is needed to join the dots. Food systems enabling fruits and vegetables in healthy diets are not only a technical issue, but bring up very real political, social and ethical questions that societies will have to address, alongside a reliance on evidence. Having these conversations through the lens of equity to address the needs of both winners and losers of food systems change will be a vital part of the UNFSS process towards enabling fruit and vegetable-rich food systems for healthy diets for all.

REFERENCES

1. FAO. The State of Food Security and Nutrition in the World. Food and Agriculture Organisation; 2020.
2. Willett W, Rockstrom J, ..., Murray CJL. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet. Feb 2 2019;393(10170):447-492. doi:10.1016/s0140-6736(18)31788-4
3. Loken B, Opperman J, Orr S, et al. Bending the Curve: The restorative power of planet-based diets. 2020. WWF Food Practice.
4. Afshin A, Sur PJ, Fay KA, ..., Murray CJL. Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet. 2019;393(10184):1958-1972. doi:10.1016/S0140-6736(19)30041-8
5. World Health Organisation. Diet, nutrition and the prevention of chronic diseases. 2003. WHO technical report series 916.
6. Herforth A, Arimond M, Álvarez-Sánchez C, Coates J, Christianson K, Muehlhoff E. A global review of food-based dietary guidelines. Advances in Nutrition. 2019;10(4):590-605.
7. Kalmpourtzidou A, Eilander A, Talsma EF. Global Vegetable Intake and Supply Compared to Recommendations: A Systematic Review. Nutrients. 2020;12(6):1558.
8. Frank SM, Webster J, McKenzie B, et al. Consumption of fruits and vegetables among individuals 15 years and older in 28 low-and middle-income countries. The Journal of nutrition. 2019;149(7):1252-1259.
9. Micha R, Khatibzadeh S, Shi P, Andrews KG, Engell RE, Mozaffarian D. Global, regional and national consumption of major food groups in 1990 and 2010: a systematic analysis including 266 country-specific nutrition surveys worldwide. BMJ open. 2015;5(9):e008705.
10. Popkin BM, Corvalan C, Grummer-Strawn LM. Dynamics of the double burden of malnutrition and the changing nutrition reality. The Lancet. 2020;395(10217):65-74.
11. Global Panel on Agriculture and Food Systems for Nutrition. Food systems and diets: Facing the challenges of the 21st Century. 2016. http://www.glopan.org/foresight
12. Hall JN, Moore S, Harper SB, Lynch JW. Global variability in fruit and vegetable consumption. Am J Prev Med. May 2009;36(5):402-409.e5. doi:10.1016/j.amepre.2009.01.029
13. Ruel MT, Nicholas M, Lisa S. Patterns and determinants of fruit and vegetable consumption in sub-Saharan Africa. 2004. FAO/WHO workshop on fruits and vegetables for health.
14. Mayen A-L, Marques-Vidal P, Paccaud F, Bovet P, Stringhini S. Socioeconomic determinants of dietary patterns in low-and middle-income countries: a systematic review. The American journal of clinical nutrition. 2014;100(6):1520-1531.
15. Harris J, Tan W, Mitchell B, Zayed D. Equity in agriculture-nutrition-health research: A scoping review. Nutrition Reviews. 2021;(accepted for publication)
16. HLPE. Nutrition and food systems. 2017.
17. Pingali PL. Green revolution: impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences. 2012;109(31):12302-12308.
18. Herforth A. Three billion people cannot afford a healthy diet: What does this mean for the next Green Revolution? Center for Strategic and International Studies commentary blog. September 23, 2020, 2020. https://www.csis.org/analysis/three-billion-people-cannot-afford-healthy-diets-what-does-mean-next-green-revolution
19. McDermott J, De Brauw A. National Food Systems: Inclusive transformation for healthier diets. IFPRI book chapters. 2020:202054-202065.
20. Masters WA, Bai Y, Herforth A, et al. Measuring the affordability of nutritious diets in Africa: price indexes for diet diversity and the cost of nutrient adequacy. American journal of agricultural economics. 2018;100(5):1285-1301.
21. Thar C-M, Jackson R, Swinburn B, Mhurchu CN. A review of the uses and reliability of food balance sheets in health research. Nutrition reviews. 2020;78(12):989-1000.
22. Harris J, Tan W, Raneri J, Schreinemachers P, Herforth A. Vegetables in food systems for healthy diets in low- and middle-income countries: Mapping the literature Forthcoming. 2021;
23. Magnan A. Food regimes. The Oxford handbook of food history. 2012:370-388.
24. Lang T, Heasman M. Food wars: the global battle for mouths, minds and markets. Routledge; 2015.

25. Thow AM, Snowdon W, Labonté R, et al. Will the next generation of preferential trade and investment agreements undermine prevention of noncommunicable diseases? A prospective policy analysis of the Trans Pacific Partnership Agreement. Health Policy. 2015;119(1):88-96.
26. Howard PH. Concentration and power in the food system: Who controls what we eat? vol 3. Bloomsbury Publishing; 2016.
27. Savary S, Akter S, Almekinders C, et al. Mapping disruption and resilience mechanisms in food systems. Food Security. 2020;12(4):695-717.
28. Block SA, Kiess L, Webb P, et al. Macro shocks and micro outcomes: child nutrition during Indonesia's crisis. Economics & Human Biology. 2004;2(1):21-44.
29. Darnton-Hill I, Cogill B. Maternal and young child nutrition adversely affected by external shocks such as increasing global food prices. The Journal of nutrition. 2010;140(1):162S-169S.
30. Harris J. Diets in a time of coronavirus: Don't let vegetables fall off the plate. IFPRI Covid-19 blogs blog. April 13, 2020, 2020. https://www.ifpri.org/blog/diets-time-coronavirus-dont-let-vegetables-fall-plate
31. Harris J, Depenbusch L, Pal AA, Nair RM, Ramasamy S. Food system disruption: initial livelihood and dietary effects of COVID-19 on vegetable producers in India. Food Security. 2020;12(4):841-851.
32. Hirvonen K, Mohammed B, Minten B, Tamru S. Food marketing margins during the COVID-19 pandemic: Evidence from vegetables in Ethiopia. vol 150. Intl Food Policy Res Inst; 2020.
33. Carducci B, Keats E, Ruel M, Haddad L, Osendarp S, Bhutta Z. Food systems, diets and nutrition in the wake of COVID-19. Nature Food. 2021;2(2):68-70.
34. Kansiime MK, Tambo JA, Mugambi I, Bundi M, Kara A, Owuor C. COVID-19 implications on household income and food security in Kenya and Uganda: Findings from a rapid assessment. World development. 2021;137:105199.
35. Goldin I, Muggah R. COVID-19 is increasing multiple kinds of inequality. Here's what we can do about it. 2020:
36. Leach M, Nisbett N, Cabral L, Harris J, Hossain N, Thompson J. Food politics and development. World Development. 2020;134:105024.
37. Rosset PM, Altieri MA. Agroecology: science and politics. Practical Action Publishing; 2017.
38. Vivero-Pol JL, Ferrando T, De Schutter O, Mattei U. Routledge handbook of food as a commons. Routledge; 2018.
39. Patnaik. B, Oenema. S. The human right to nutrition security in the post-2015 development agenda. SCN News. 2015;41:69-73.
40. Harris J. Coalitions of the willing? Advocacy coalitions and the transfer of nutrition policy to Zambia. Health Policy and Planning. 2019;34(3):207-215.
41. Chaudhury M, Vervoort J, Kristjanson P, Ericksen P, Ainslie A. Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. Regional Environmental Change. 2013;13(2):389-398.
42. Barzola CL, Dentoni D, Allievi F, et al. Challenges of youth involvement in sustainable food systems: Lessons learned from the case of farmers' value network embeddedness in Ugandan Multi-Stakeholder Platforms. Achieving the Sustainable Development Goals Through Sustainable Food Systems. Springer; 2019:113-129.
43. Blay-Palmer A, Santini G, Dubbeling M, Renting H, Taguchi M, Giordano T. Validating the city region food system approach: Enacting inclusive, transformational city region food systems. Sustainability. 2018;10(5):1680.
44. Béné C, Oosterveer P, Lamotte L, et al. When food systems meet sustainability – Current narratives and implications for actions. World Development. 2019;113:116-130.
45. Thow AM, Verma G, Soni D, et al. How can health, agriculture and economic policy actors work together to enhance the external food environment for fruit and vegetables? A qualitative policy analysis in India. Food Policy. 2018;77:143-151.
46. Mogues T, Yu B, Fan S, McBride L. The impacts of public investment in and for agriculture: Synthesis of the existing evidence. 2012;
47. Baker P, Machado P, Santos T, et al. Ultra-processed foods and the nutrition transition: Global, regional and national trends, food systems transformations and political economy drivers. Obesity Reviews. 2020;21(12):e13126.
48. Knai C, Pomerleau J, Lock K, McKee M. Getting children to eat more fruit and vegetables: a systematic review. Preventive medicine. 2006;42(2):85-95.
49. Micha R, Karageorgou D, Bakogianni I, et al. Effectiveness of school food environment policies on children's dietary behaviors: A systematic review and meta-analysis. PloS one. 2018;13(3):e0194555.
50. Vandevijvere S, Barquera S, Caceres G, et al. An 11-country study to benchmark the implementation of recommended nutrition policies by national governments using the Healthy Food Environment Policy Index, 2015-2018. Obesity Reviews. 2019;20:57-66.
51. Sunderland TC, Vasquez W. Forest Conservation, Rights, and Diets: Untangling the Issues. Frontiers in Forests and Global Change. 2020;3:29.
52. Mason-D'Croz D, Bogard JR, Sulser TB, et al. Gaps between fruit and vegetable production, demand,

and recommended consumption at global and national levels: an integrated modelling study. The Lancet Planetary Health. 2019;3(7):e318-e329.
53. Schreinemachers P, Simmons EB, Wopereis MC. Tapping the economic and nutritional power of vegetables. Global food security. 2018;16:36-45.
54. Springmann M, Spajic L, Clark MA, et al. The healthiness and sustainability of national and global food based dietary guidelines: modelling study. bmj. 2020;370
55. Aleksandrowicz L, Green R, Joy EJ, Smith P, Haines A. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PloS one. 2016;11(11):e0165797.
56. Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F, Leip A. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food. 2021:1-12.
57. Schreinemachers P, Grovermann C, Praneetvatakul S, et al. How much is too much? Quantifying pesticide overuse in vegetable production in Southeast Asia. Journal of Cleaner Production. 2020;244:118738.
58. Grace D. Food safety in low and middle income countries. International journal of environmental research and public health. 2015;12(9):10490-10507.
59. Dawson IK, Powell W, Hendre P, et al. The role of genetics in mainstreaming the production of new and orphan crops to diversify food systems and support human nutrition. New Phytologist. 2019;224(1):37-54.
60. Schreinemachers P, Howard J, Turner M, et al. Africa's evolving vegetable seed sector: status, policy options and lessons from Asia. Food Security. 2021:1-13.
61. Lillesø J-PB, Harwood C, Derero A, et al. Why institutional environments for agroforestry seed systems matter. Development Policy Review. 2018;36:O89-O112.
62. Phillips C. Saving more than seeds: Practices and politics of seed saving. Routledge; 2016.
63. Gupta A, Negi P. Protection of 'Plant Varieties' Vs. Balancing of rights of Breeders and Farmers. International Journal of Reviews and Research in Social Sciences. 2019;7(4):741-745.
64. Salazar R, Louwaars NP, Visser B. Protecting farmers' new varieties: new approaches to rights on collective innovations in plant genetic resources. World Development. 2007;35(9):1515-1528.
65. Dias JCS. Biodiversity and vegetable breeding in the light of developments in intellectual property rights. Ecosystems biodiversity. 2011:389-428.
66. Weinberger K, Lumpkin TA. Diversification into horticulture and poverty reduction: a research agenda. World development. 2007;35(8):1464-1480.
67. Herrero M, Thornton PK, Power B, et al. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. The Lancet Planetary Health. 2017;1(1):e33-e42.
68. Pingali P. Agricultural policy and nutrition outcomes – getting beyond the preoccupation with staple grains. Article. Food Secur. 2015;7(3):583-591. doi:10.1007/s12571-015-0461-x
69. Dolislager M, Reardon T, Arslan A, et al. Youth and adult agrifood system employment in developing regions: Rural (peri-urban to hinterland) vs. urban. The Journal of Development Studies. 2020:1-23.
70. Reardon T, Tschirley D, Dolislager M, Snyder J, Hu C, White S. Urbanization, Diet Change, and Transformation of Food Supply Chains in Asia. 2014. Global Centre for Food Systems Innovation.
71. HLPE. Food losses and waste in the context of sustainable food systems. High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security; 2014.
72. Global Panel. Preventing nutrient loss and waste across the food system: Policy actions for high-quality diets. Policy Brief No. 12, November 2018. 2018.
73. FAO. Moving forward on food loss and waste reduction. . 2019. The State of Food and Agriculture 2019
74. Schreinemachers P, Patalagsa MA, Islam MR, et al. The effect of women's home gardens on vegetable production and consumption in Bangladesh. Food Security. 2015;7(1):97-107.
75. Bharucha Z, Pretty J. The roles and values of wild foods in agricultural systems. Philosophical Transactions of the Royal Society B: Biological Sciences. 2010;365(1554):2913-2926.
76. Raihana AN, Marikkar J, Amin I, Shuhaimi M. A review on food values of selected tropical fruits' seeds. International Journal of Food Properties. 2015;18(11):2380-2392.
77. Hunter D, Borelli T, Beltrame DM, et al. The potential of neglected and underutilized species for improving diets and nutrition. Planta. 2019;250(3):709-729.
78. Gilbert CL, Christiaensen L, Kaminski J. Food price seasonality in Africa: Measurement and extent. Food policy. 2017;67:119-132. doi:10.1016/j.foodpol.2016.09.016
79. McMullin S, Njogu K, Wekesa B, et al. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: A new approach for providing year-round micronutrients to smallholder farmers. Food Security. 2019;11(6):1355-1372.

80. Godfray HCJ, Garnett T. Food security and sustainable intensification. Philosophical transactions of the Royal Society B: biological sciences. 2014;369(1639):20120273.
81. Knapp S, van der Heijden MG. A global meta-analysis of yield stability in organic and conservation agriculture. Nature communications. 2018;9(1):1-9.
82. Reardon T, Timmer CP. Five inter-linked transformations in the Asian agrifood economy: Food security implications. Global Food Security. 2014;3(2):108-117.
83. FAO. FRUIT AND VEGETABLES – YOUR DIETARY ESSENTIALS 2021. The International Year of Fruits and Vegetables 2021 - Background paper. http://www.fao.org/3/cb2395en/CB2395EN.pdf
84. Fischer G, Gramzow A, Laizer A. Gender, vegetable value chains, income distribution and access to resources: insights from surveys in Tanzania. European Journal of Horticultural Science. 2017;82(6):319-327.
85. Gassner A, Harris D, Mausch K, et al. Poverty eradication and food security through agriculture in Africa: Rethinking objectives and entry points. Outlook on Agriculture. 2019;48(4):309-315.
86. Reardon T, Chen KZ, Minten B, Adriano L. The quiet revolution in staple food value chains in Asia: enter the dragon, the elephant, and the tiger. Asian Development Bank and International Food Policy Research Institute, Philippines. 2012;
87. Holtland G, ed. Contract farming in Ethiopia: Concept and practice. AgriProFocus; 2017.
88. Carletto C, Corral P, Guelfi A. Agricultural commercialization and nutrition revisited: Empirical evidence from three African countries. Food Policy. 2017;67:106-118.
89. Wohner B, Pauer E, Heinrich V, Tacker M. Packaging-related food losses and waste: an overview of drivers and issues. Sustainability. 2019;11(1):264.
90. Yates J, Deeney M, Rolker HB, White H, Kalamatianou S, Kadiyala S. A systematic scoping review of environmental, food security and health impacts of food system plastics. Nature Food. 2021;2(2):80-87.
91. Ghosh-Dastidar B, Cohen D, Hunter G, et al. Distance to store, food prices, and obesity in urban food deserts. American journal of preventive medicine. 2014;47(5):587-595. doi:10.1016/j.amepre.2014.07.005
92. Beaulac J, Kristjansson E, Cummins S. A systematic review of food deserts, 1966-2007. Preventing chronic disease. 2009;6(3)
93. Ambikapathi R, Shively G, Leyna G, et al. Informal food environment is associated with household vegetable purchase patterns and dietary intake in the DECIDE study: Empirical evidence from food vendor mapping in peri-urban Dar es Salaam, Tanzania. Global Food Security. 2021;28:100474.
94. Gissing SC, Pradeilles R, Osei-Kwasi HA, Cohen E, Holdsworth M. Drivers of dietary behaviours in women living in urban Africa: a systematic mapping review. Public health nutrition. 2017;20(12):2104-2113.
95. Maillot M, Darmon N, Darmon M, Lafay L, Drewnowski A. Nutrient-dense food groups have high energy costs: an econometric approach to nutrient profiling. J Nutr. Jul 2007;137(7):1815-20. doi:10.1093/jn/137.7.1815
96. Headey DD, Alderman HH. The Relative Caloric Prices of Healthy and Unhealthy Foods Differ Systematically across Income Levels and Continents. The Journal of Nutrition. 2019;doi:10.1093/jn/nxz158
97. Herforth A, Bai Y, Venkat A, Mahrt K, Ebel A, Masters W. Cost and affordability of healthy diets across and within countries: Background paper for The State of Food Security and Nutrition in the World 2020. FAO Agricultural Development Economics Technical Study No. 9. vol 9. Food & Agriculture Org.; 2020.
98. Drewnowski A. New metrics of affordable nutrition: which vegetables provide most nutrients for least cost? J Acad Nutr Diet. 2013;113(9):1182-1187.
99. Miller V, Yusuf S, Chow CK, et al. Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the Prospective Urban Rural Epidemiology (PURE) study. The Lancet Global Health. 2016;4(10):e695-e703. doi:10.1016/s2214-109x(16)30186-3
100. Morris S, Haddad L. Selling to the world's poorest - the potential role of markets in increasing access to nutritious foods. 2020. GAIN Working Paper Series 14.
101. Aggarwal A, Rehm CD, Monsivais P, Drewnowski A. Importance of taste, nutrition, cost and convenience in relation to diet quality: Evidence of nutrition resilience among US adults using National Health and Nutrition Examination Survey (NHANES) 2007–2010. Preventive Medicine. 2016/09/01/ 2016;90:184-192.
102. Ha TM, Shakur S, Pham Do KH. Risk perception and its impact on vegetable consumption: A case study from Hanoi, Vietnam. Journal of Cleaner Production. 2020/10/20/ 2020;271:122793.
103. Hammelman C, Hayes-Conroy A. Understanding Cultural Acceptability for Urban Food Policy. Journal of Planning Literature. 2015/02/01 2014;30(1):37-48. doi:10.1177/0885412214555433
104. FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World 2019.

Safeguarding against economic slowdowns and downturns. FAO; 2019.
105. Hirvonen K, Bai Y, Headey D, Masters WA. Cost and affordability of the EAT-Lancet diet in 159 countries. Lancet. 2019;
106. Benton TG, Bieg C, Harwatt H, Pudasaini R, Wellesley L. Food System Impacts on Biodiversity Loss. 2021. Research Paper: Energy, Environment and Resources Programme.
107. Niebylski ML, Redburn KA, Duhaney T, Campbell NR. Healthy food subsidies and unhealthy food taxation: A systematic review of the evidence. Nutrition. 2015/06/01/ 2015;31(6):787-795.
108. Swinburn BA, Kraak VI, Allender S, et al. The global syndemic of obesity, undernutrition, and climate change: the Lancet Commission report. The Lancet. 2019;393(10173):791-846.
109. Olsho LE, Klerman JA, Wilde PE, Bartlett S. Financial incentives increase fruit and vegetable intake among Supplemental Nutrition Assistance Program participants: a randomized controlled trial of the USDA Healthy Incentives Pilot. The American journal of clinical nutrition. 2016;104(2):423-435.
110. Schreinemachers P, Patalagsa MA, Uddin N. Impact and cost-effectiveness of women's training in home gardening and nutrition in Bangladesh. Journal of Development Effectiveness. 2016;8(4):473-488. doi:10.1080/19439342.2016.1231704
111. Baliki G, Brück T, Schreinemachers P, Uddin MN. Long-term behavioural impact of an integrated home garden intervention: evidence from Bangladesh. Food Security. 2019/09/03 2019;11:1217-1230. doi:10.1007/s12571-019-00969-0
112. Powell B, Thilsted SH, Ickowitz A, Termote C, Sunderland T, Herforth A. Improving diets with wild and cultivated biodiversity from across the landscape. Food Security. 2015;7(3):535-554.
113. Alderman H, Headey DD. How important is parental education for child nutrition? World Development. 2017;94:448-464.
114. Eker S, Reese G, Obersteiner M. Modelling the drivers of a widespread shift to sustainable diets. Nature Sustainability. 2019;2(8):725-735.
115. Van den Bold M, Quisumbing AR, Gillespie S. Women s Empowerment and Nutrition: An Evidence Review. vol 1294. Intl Food Policy Res Inst; 2013.
116. Pedersen C, Remans R, Zornetzer H, et al. Game-changing innovations for healthy diets on a healthy planet: Insights from a Delphi Study. 2020;
117. Davis KF, Downs S, Gephart JA. Towards food supply chain resilience to environmental shocks. Nature Food. 2021;2(1):54-65.
118. Stadlmayr B, Charrondiere UR, Eisenwagen S, Jamnadass R, Kehlenbeck K. Nutrient composition of selected indigenous fruits from sub-Saharan Africa. Journal of the Science of Food and Agriculture. 2013;93(11):2627-2636.
119. Jansen M, Guariguata MR, Raneri JE, et al. Food for thought: The underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems. People and Nature. 2020;2(4):1006-1020.
120. Broers VJ, De Breucker C, Van den Broucke S, Luminet O. A systematic review and meta-analysis of the effectiveness of nudging to increase fruit and vegetable choice. The European Journal of Public Health. 2017;27(5):912-920.
121. Schreinemachers P, Baliki G, Shrestha RM, et al. Nudging children toward healthier food choices: An experiment combining school and home gardens. Global Food Security. 2020;26:100454.
122. Bublitz MG, Peracchio LA. Applying industry practices to promote healthy foods: An exploration of positive marketing outcomes. Journal of Business Research. 2015/12/01/ 2015;68(12):2484-2493.
123. Thomson CA, Ravia J. A systematic review of behavioral interventions to promote intake of fruit and vegetables. Journal of the American Dietetic Association. 2011;111(10):1523-1535.
124. Deo A, Monterrosa E. Demand creation at GAIN. 2020.
125. Harris J, Nisbett N. Equity in social and development studies research: What insights for nutrition? SCN News. 2018;43
126. Wiebe K, Prager S. Commentary on foresight and trade-off analysis for agriculture and food systems. Q Open. 2021;1(1):qoaa004.

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

ADVANCE EQUITABLE LIVELIHOODS - A PAPER ON ACTION TRACK 4 -

by Lynnette M. Neufeld, Jikun Huang, Ousmane Badiane, Patrick Caron, Lisa Sennerby Forsse

ABSTRACT

Food systems transformation provides the opportunity to shift current trends in all forms of malnutrition, prioritizing nutritious food availability and affordability for all – from shifting priorities in agricultural production, to improved food systems that favor nutrition and sustainability. The task of Action Track 4 is to explore approaches to doing so that will advance equitable livelihoods for producers, businesses, workers across the food system and consumers, with a particular emphasis on addressing inequalities and power

THE AUTHORS ARE

Lynnette M. Neufeld (Canada) Incoming President of the International Union of Nutrition Scientists (IUNS), Director Knowledge Leadership, Global Alliance for Improved Nutrition (GAIN).

Jikun Huang (China) Professor at School of Advanced Agricultural Sciences and Director of China Center for Agricultural Policy (CCAP), Peking University.

Ousmane Badiane (Senegal) Chairperson of Akademiya2063, former Africa Director for the International Food Policy Research Institute (IFPRI).

Patrick Caron (France) Vice-President of the University of Montpellier, President of Agropolis International and Director of the Montpellier Advanced Knowledge Institute on Transitions.

Lisa Sennerby Forsse (Sweden) Past President, Royal Swedish Academy of Agriculture and Forestry (KSLA) and Vice-Chancellor of the Swedish University of Agricultural Sciences 2006-2015.

imbalances. As the Science Group for AT 4, we explore the nature of these issues, using the drivers of food systems as articulated by the High-Level Panel of Experts of the UN Committee on World Food Security as framing. Small and medium-sized producers and people living on the food system in rural and urban areas are disproportionately affected by all **biophysical and environmental drivers** including soil and water resources, and climate change. Unequal opportunity in access to all types of resources reduces overall production, resilience, rural transformation. Advances in innovation, technology and infrastructure have had important impacts on food production and sustainability, transportation and processing along food value chains, marketing, and ultimately diets, including consumption of both nutritious and unhealthy foods. However, achievement of equitable livelihoods in food systems will require that issues of access to contextually suitable innovation and technology, inclusive of indigenous knowledge, be substantially enhanced. Many **economic and political factors** can be essential causes of inequality and power imbalances at household, community, national and global levels, which may constrain the ability of food systems transformation to deliver poverty reduction and sustainable, equitable livelihoods. Finally, vast evidence illustrates that several **socio-cultural and demographic drivers** underpin inequalities among and within societies and constrain the potential for some to benefit from actions to improve livelihoods, particularly women, youth, disabled, elderly, and indigenous peoples. These issues are exacerbated by the COVID-19 pandemic. The pandemic is having a significant impact on the global commodity markets and trading systems, economic growth, incomes, and poverty levels, with likely disproportionate burden on the vulnerable communities in both urban and rural areas. This is likely to worsen inequalities and set back progress against poverty and hunger goals. To address these issues, we must transform not only food systems, but the structures and systems that continue to enable and exacerbate inequities. Drivers of food systems inequities are highly interconnected and progress to address one will likely require change across several. For example, globalization and trade interact with other powerful drivers, especially technology resource mobilization, and demographic trends, which shape food production, distribution, and consumption. Hence, in the final section we reflect on several factors that should be part of effective solutions to combat inequalities in food systems, including rights-based approaches. We then share a series of recommendations aimed to enhance inclusive decision-making, protect the livelihoods of those living in situations of vulnerability while creating opportunities, adapting institutions and policies to favor equitable food systems livelihoods, and increasing investment to realize the potential of improved institutional and policy actions. We invite governments, businesses, and organizations to hold themselves and others to account for advancing equitable livelihoods, and open avenues to realize the potential of science, innovation, technology, and evidence to favor equitable livelihoods.

INTRODUCTION

Food systems transformation provides the opportunity to shift current trends in all forms of malnutrition, prioritizing nutritious food availability and affordability for all – from shifting priorities in agricultural production, to improved food systems that favor nutrition and sustainability.

The purpose of the Action Track 4 science group is to provide the scientific basis for the work of the Action Track (AT). Our task as the science group encompasses reviewing the evidence that studies the nature of the issues and the evidence that underpins potential solutions. It also helps identifying uncertainty and gaps in knowledge. The central issue identified by the AT 4 team has been stated as:

> *Inequality and power imbalances – at household, community, national and global levels – are consistently constraining the ability of food systems to deliver poverty reduction and sustainable, equitable livelihoods.*

In developing solutions, AT 4 explicitly calls out inequities related to gender, youth, elderly, minority, migrant, and indigenous peoples. These solutions focus on small and medium size enterprises (SMEs) across the food value chain, but also equitable access to employment and livelihoods for wage earners, extending the concerns of inequality to rural/ urban and other social and geographic divides. Efforts to address inequality and power imbalances must build agency, change relations, and transform the structures that underpin this imbalance of power and result in inequalities, as illustrated in the Figure 1.

The most effective way to sustainably eradicate poverty and inequality is to boost the opportunities and capacities of the poor and those living in situations of vulnerability, through redistributing resources more equitably (e.g., land, incomes, social protection), ensuring quality education, progressive and not regressive taxation, state infrastructure investments among

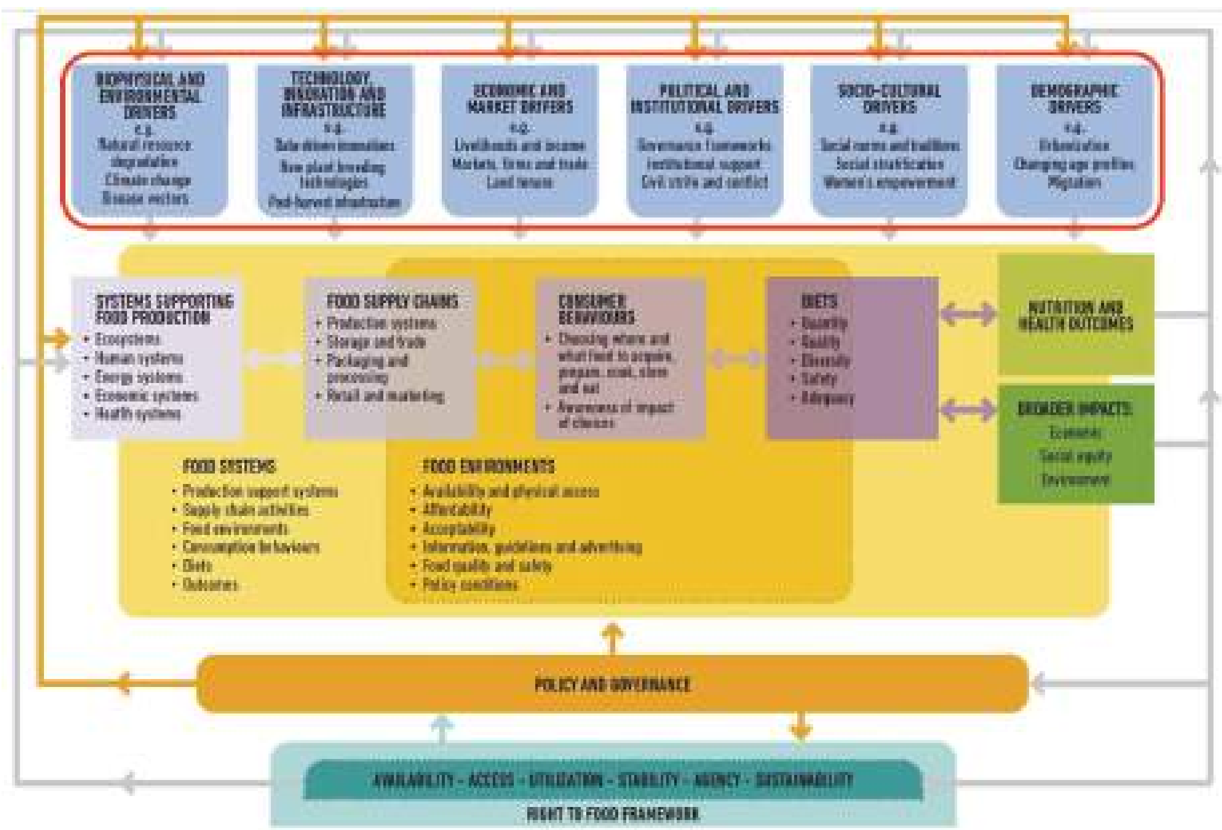
Figure 1

(Figure credit: Action Track 4 Discussion Starter, October 2020)

other approaches. Reducing inequalities requires that gains in productivity, production and income be assessed against their positive impact on marginalized groups. Decision-making must also become more participatory and accountable to those who are most negatively affected by our current food system and their outcomes. Progress in advancing equitable livelihoods and value distribution therefore involve several key areas ranging from expanding access to assets, infrastructure, and services as well as other required measures to enhance quality of living spaces. Interventions to produce real change on the ground need to empower the poor and those living in situations of vulnerability.

To fulfill our task as the science group, we need to step back and consider the evidence related to the drivers of inequality and power imbalances as they relate to livelihoods across the food system. We use the conceptual framework of food systems developed by the High-Level Panel of Experts of the UN Committee on world Food Security in 2017, and updated in 2020, and structure this review around the six drivers of food systems (as highlighted in the red box of Figure 2).

Figure 2 Conceptual framework of sustainable food systems (reduced from HLPE1)



Framed around the drivers of sustainable food systems (combining them where the nature of the evidence warrants), the following sections provide an overview of the nature of the issue as it relates to drivers of inequality and power imbalances. Our intent is to explore these drivers as they relate to livelihoods among those living in situations of vulnerability, including consumers and producers and all types of workers across all food systems types and contexts (see for definitions and concepts related to food systems). In the final section, we provide examples from the literature that can inform potential solutions to address the issues.

1. Biophysical and environmental drivers, particularly soil, water, and climate change:

In rural areas of many low- and middle-income countries (LMICs), natural resources are an important source of food, both through direct consumption and through providing the basis for income generating activities (e.g., food and no-food cash crops, forest, and fishery products). Access to natural resources like land, water, forests, and fisheries is a key element of livelihood strategies ("natural capital"), together with other elements such as access to employment and/or credit ("financial capital"). Because of this, measures to improve access to resources are an important element of strategies for the realization of the right to food (see conclusion section below for further discussion). Small and medium-sized producers and people living on the food system in rural and urban areas are disproportionately affected by all biophysical and environmental drivers including soil and water resources. Inequal opportunities to access all types of resources defers overall production, resilience, rural transformation, thus directly affecting the livelihoods of all actors across food value chains via diverse pathways.

The number of people whose livelihoods depends on degraded lands has been estimated to be about 1.5 billion worldwide. In India, for example, 146.8 million out of the estimated 329 million hectares of total geographical area is reported as degraded. People living in degraded areas depend directly on natural resources for subsistence, food security, and income. Women and youth often have limited options and are especially vulnerable to land degradation and climate change. Land degradation reduces productivity and increases the workload of managing the land, disproportionately affecting women in some regions. Land degradation and climate change act as threat multipliers for already precarious livelihoods, with consequences for increased risks of poverty, food insecurity, and in some cases migration, conflict and loss of cultural heritage. The major anthropogenic drivers of erosion are land use and climate change, in particular through a more intense hydrological cycle. While much research attention has focused on arable agriculture, seminatural systems, such as water may account for nearly half of global soil erosion. There are many indications that water is becoming an increasingly scarce resource, a point often made over the last 10 years.Access to water is now recognized as a prerequisite for poverty reduction. However, competition for water from many different sectors can divert attention from its role in the improvement of human livelihoods.

Marine ecosystems are increasingly affected by fishing and climate change, including reduced ocean productivity, changes in species distributions, increased disease among other effects. These and the other climate related changes discussed above may be especially challenges for the security and livelihoods of coastal communities, particularly for indigenous people and those in LMICs.

Climate change is the defining issue of our time, and we are at a defining moment. From shifting weather patterns that threaten food production, to rising sea levels that increase the risk of catastrophic flooding, the impacts of climate change are global in scope and unprecedented in scale. The adverse effect of climate change and variability has become an environmental and socio-economic problem which is increasingly causing climate-driven hazards to people around the world. The effects of climate change are likely to be more serious among countries with fewer capacities to respond and adapt and, within these countries, among the poorest and most vulnerable. Climate change serves as a serious inhibitor to the attainment of food security and the fulfillment of major development agendas in the majority of global economies. Climate change could undermine social welfare, equity, and the sustainability of future development. It is generally believed that LMICs, and disadvantaged groups within all countries are more vulnerable to the impacts of climate change as a result of limited resources and low adaptive capacity.

2. Technology, Innovation, and infrastructure drivers:

For both short and long distances value chains, infrastructure strongly influences the way food is produced, processed, transported, distributed, sold, conserved, and ultimately consumed. Infrastructure is required for food to move long distances and increase food security in areas of shortages, stabilize food prices, minimize food-borne disease and food waste. Roads, railroads, shipping, and cold chain facilities play an essential role. Poorly developed infrastructure impacts all dimensions of livelihoods for urban and rural populations. It affects the quality and safety of nutritious foods particularly, limits access to nutritious foods, and exacerbates issues of food loss and waste. In South Sudan and Somalia, for example, poor road infrastructure is a major barrier to food access. Infrastructure improvements, technological advances and mechanization in the food value chain may generate positive externalities for production, trading and consumption with potential to generate off-farm employment in rural, and potentially in urban areas. Examples may include factories located near the farm where the technology will be used, technicians and mechanics to operate and repair machinery and devices, other business-related employment, such as bookkeepers, sales staff, etc. They may also generate negative externalities.

Innovation, technology and infrastructure improvements have been and will be major drivers for food system transformation. Advances in all three have had important impacts on food production and sustainability, transportation and processing along food value chains, marketing, and ultimately diets, including consumption of both nutritious and unhealthy foods. They can also generate risks to human and environmental health and may not yield equitable benefits for farmers or other food systems workers. This raises the questions of targeting technology policies and interventions according to their impact on improving livelihoods among the poor and those living in situations of vulnerability. The need to produce healthier and accessible food and address SDDG 2 and other SDGs through food systems transformation will thus require innovative, responsible, and targeted efforts by the actors in the world's food supply chains. Nonetheless, many breakthrough technologies spark disputes and sociotechnical controversies, that more and more generate dual oppositions and polarized polemics. This may distract from the goal of ensuring that the livelihood and equity impacts from modern biotechnology are widely shared. In some socio-ecological contexts, this requires measures to prevent that such technology result in market concentration in the industries that provide inputs to agriculture, prohibitively high seed prices or reduced farmer participation in breeding. It may also be necessary to ensure that the technology does not favor larger farm economic units with likely displacement of smallholder farmers. Whatever the controversial issue, evidence highlights how institutional environments are essential to direct technology and innovation impact. Ultimately, the potential for impact depends not only on characteristics of the technological advancement itself, but on access patterns, arrangements, and governance about who controls it.

Innovations in breeding methods, chemical synthetic inputs, and food processing have changed the way food is produced, stored, distributed, consumed. Many agricultural innovations have prioritized yield and productivity, with many disproportionately favoring high income country food systems, but some notable exceptions exist. Since 2004, HarvestPlus in collaboration with CGIAR centers has facilitated the release of 211 crop varieties in 30 countries that have been bred with increased content of one or more nutrients. An estimated 7.6 million farming households are now growing these crops, estimated to be benefiting some 38 million rural consumers.This number will be enhanced as crops and sold purchased in urban markets, and used in various processed or pre-prepared foods. Another example promotes the better incorporation of fruit into local food systems, meeting the challenge of seasonal availability. McMullin et al developed a methodology based on 'fruit-tree portfolios,' which selects in partnership with farmers, the fruit-tree species for production that both socio-ecologically suitable, and nutrient-rich. Both examples have the dual advantage of potentially improving livelihoods and favoring nutrition outcomes through enhanced production and access to nutritious foods. Modern biotechnology can also improve livelihoods through increased crop production for smallholder farmers. Millions of small farmers in many LMIC (e.g., China and India) have benefited from adoption of Bt cotton after this technology has been approved for commercialization since the late-1990s. Nonetheless, the impact of such technology on livelihoods, particularly for farmers in situations of vulnerability is disputed and has been shown to depend on differentiated practices. Among the issues to resolve in this regard is the ongoing debate related to access to seeds, and mechanisms to ensure that commercial interests in seed-line access do not negatively affects producers and consumers livelihood.

According to the CGIAR Research Program on Climate Change, Agriculture and Food Security, some of the most promising innovations in rural agriculture are technology- and service-based. With access to data, markets, and financial services, farmers can plant, fertilize, harvest, and sell products more effectively. These approaches are gradually gaining favor as more people in emerging economies connect to mobile networks, and applications designed to collect and share agricultural information become increasingly accessible. Of course, the mere existence of this technology will not generate better livelihoods. Access to such technology has been highly constrained and must be resolved before this potential can be realized. Similarly, tools must meet the needs of the farmers who use them and expectations towards improving livelihood, including addressing power asymmetries. This demands that mobile technologies take into account differences in gender, education, and resource levels among farmers and consumers, and are responsive to changing circumstances. The impact and success of these tools and programs should be monitored and evaluated, with ineffective approaches being improved or replaced. Capacitated endogenous institutions are vital to achieving an inclusive approach.

3. Economic and political drivers:

Many economic and political factors are essential causes of inequality and power imbalances at household, community, national and global levels, which constrain the ability of food systems transformation to deliver poverty reduction and sustainable, equitable livelihoods.Improving education and literacy levels, access to public services and infrastructure and among others helps to address the issue.

Social protection is a menu of policy instruments to address poverty and vulnerability, through social assistance, social insurance and efforts at social inclusion, with a role to address both long-standing and crisis-induced poverty. The precarity of the food system in most countries, and particularly food systems workers living in situations of vulnerability is illustrated by the current COVID-19 crisis (Box 1). The lessons and experience from global efforts fighting the COVID-19 pandemic show the importance of developing a strong social network in coping with fragility of food system.

Conflicts and crises, usually resulting from an unstable political system and uncertain property right arrangements, damage trust and social cohesion among the stakeholders throughout the food systems, discourage public and private investment and cause slowdown in economic growth and less inclusive rural and structural transformations. This does harm to vulnerable smallholder farmers, consumers and those engaged in micro enterprises and SMEs along food value chains, and particularly those run by and employing youth, women, disabled, and indigenous peoples.

Inclusive development of food systems is also constrained by lack of representative **leadership**, reflected in inequality in access to productive resources, working opportunities, market participation rights and public services. Studies in almost all LMIC contexts, except Latin America and the Caribbean, indicate a large proportion of total farmland belongs to small holders (less than 2 ha), and that here and for all food systems workers, resources and public services are unequally allocated. Barriers to active participation in leadership and decision-making must be broken down.

Livelihood inequalities across the food system, including among smallholder farmers, small business, and workers across the food value chain can be reduced only if inequalities in **access to land, water, employment**, financial services, infrastructure, technology, markets, and other economic opportunities are resolved. Food system transformation that does not address these inequalities and specific vulnerabilities runs the risk of reinforcing and deepening inequalities into the future and undermining the resilience of food systems. Inequitable economic opportunities are usually caused by rigid institutional arrangements in land, water, credit, and labor markets, lack of information, market segregation/ monopoly, discriminative treatment, and distorted policies, among others. Subdivision among siblings make it harder for rural youth to obtain as much land as their parents had; in many contexts youth have historically marginalized economically, socially and politically. Research shows that respecting/upholding collective forms of land ownership and customary property regimes has important positive implications for livelihood equity However, the nature of public goods such as water resources makes fair allocation difficult. Removing barriers to employment and other economic opportunities in addition to various actions to reduce discrimination towards migrant workers also work to increase income and improve livelihoods.

As pointed out by the HLPE, **globalization and trade** have a critical role to play in ensuring food security and nutrition (FSN) and reducing inequalities. Trade can positively and negatively affect all four pillars of FSN (availability, access, utilization, stability). Evidence suggests that globalization and international trade may help to extend the value chain and generate opportunities to create wealth and equitable livelihoods among countries. International trade and financial flows are also associated with changes in production and consumption patterns that require taking into account the way livelihood is affected, in particular through employment access, incomes and wealth distribution. Measures are needed to avoid unwanted outcomes, including increases in income inequality. While some farmers can improve their livelihoods by tapping into exportable agricultural production, considerable research shows that becoming part of export markets can make farmers, particularly small-scale farmers more vulnerable to shocks in global commodity markets. These risks can be mitigated through collective action and policy support to soften the impact of such shocks among smallholders and other actors in the food system that lack the capacity to respond adequately.

Stabilizing food prices will help to reduce the risk of all stakeholders along the food supply chains and will bring benefits to the small holders who are more vulnerable in the production system and consumers in rural and urban. In general, food supply is much more stable at the regional and global levels than it is within a given country. This is because an efficient market provides the opportunity to supplement supplies in cases of domestic production shortfall or rapidly expanding demand and thereby help prevent sharp prices increases that would affect access to food negatively. Inversely, in cases where rising domestic supplies threaten to depress local prices, an appropriate political regulation and management of stocks (at both national and international dimension), plus a transparent trade mechanism, calling for an appropriate political regulation and management of stocks, for which a regional and/or global dimension is appropriate.

The informal food processing sector has grown significantly over the last decade, thanks to rapid urbanization and growing middle class, and has become one of the most dynamic segments of food staples value chains. In Africa, it is currently the fastest growing export sector, both to regional and outside markets. It is estimated that upward of two-thirds of staples food consumed in Africa by 2040 will be in processed form. The emerging staples food processing sector is currently characterized by a large and growing number of primarily female headed small enterprises. Future strategies to promote equitable livelihoods and value distribution in domestic food systems will need to reverse the current formality and size bias in order to tap into the employment and income opportunities resulting from the rapidly transforming staples value chains for the benefits of farmers, unskilled workers, and consumers in urban centers and rural towns.

These political and economic factors may cause inequality and imbalances through a complex mechanism but may also be the consequence of such inequality and imbalance. On the one hand, both political instability and poor economic performance are believed contributing to rural poverty and inequality of livelihood in rural sectors of many LMICs in all regions. On the other hand, a burgeoning literature illustrates that rapid economic growth is not a sufficient condition for inclusive development. In addition, the political and economic drivers may also interact with innovation, technology and infrastructure to influence food systems as well as inequality and power imbalances related to gender, youth, smallholders and indigenous people. Consequently, the question is not only whether but also how economic growth and institutional/policy arrangements may affect inequality in access to production, employment and fair share opportunity. This calls for considering the way agency conditions or prevents the development of inclusive, equitable livelihoods, in particular through access to the public services, before proper decision-making and agenda setting could be made.

The pace of future improvement in livelihoods will depend on the ability of governments to find ways to maximize the impact of economic growth and investments in social sectors, such as health, education, social protection on enhancing capacities among the poor and vulnerable. This not only calls for better coordination of interventions across government but also recognition and effective exploitation of that fact that differences in services and how they are bundled produce different impacts on livelihood of the poor and those living in vulnerable situations. For instance, the impact of a given dollar amount spent on education services on smallholder and low skilled off-farm and urban labor productivity will depend on the extent to which it targets vocational training and other efforts to upgrade and develop skills in the relevant sectors. Against the background of the current COVID-19 pandemic, the same concept can be illustrated using the example of health services (Box 1). Furthermore, there is evidence that morbidity has a bigger impact on productivity of the poor and vulnerable than among better off segments of the population. It has also been shown that different types of health services have different impact on disease prevalence and morbidity. It is therefore possible to allocate public investment in health services such as to target diseases that have the largest effects on the productivity of smallholders and low skilled laborers and excluded communities. Allen and co-authors show that morbidity not only affects labor availability and productivity, but it also affects the choice of technologies and returns to use of fertilizers and mechanization. More importantly, different health services have different impact on disease prevalence which affects efficiency and thus livelihoods differently even among the poor, those living in vulnerable situations, and across gender. The current COVID-19 pandemic illustrates the need and opportunity to rethink the delivery of social services in order to maximize their benefit and impact among the poor and vulnerable (Box 1). This applies equally to social protection policies where the experience of productive safety nets in Ethiopia offers valuable lessons in designing programs that work for the poor and vulnerable.

4. Socio-cultural and Demographic drivers:
Vast evidence illustrates that several socio-cultural drivers underpin inequalities among and within societies and constrain the potential for some to benefit from actions to improve livelihoods, particularly women, youth, disabled, elderly, and indigenous peoples. For example, there are approximately 185 million indigenous women in the world, belonging to more than 5,000 different indigenous peoples. Despite the broad international consensus about the important role indigenous women play in eradicating hunger and malnutrition, there are still limitations in the recognition and exercise of their rights. Due to the long-term and ongoing impacts of colonialism and environmental degradation, many indigenous peoples, regardless of their geographic location, face high levels of obesity and chronic disease and are disproportionally affected by poverty and food insecurity. Past and present social and environmental injustices have led to the loss of food sovereignty, through dispossessing indigenous peoples from their traditional territories and undermining intergenerational knowledge transmission of cultural practices related to their food systems and have been linked, as in the case of the experience of hunger in residential schools in Canada, to the rise of diabetes in these populations.

Socio-cultural drivers also impact and set the norms for the dynamics of the other drivers, including political and economic drivers, demography, innovation/ technology, among others. As such, structural barriers for several groups particularly women and youth include land rights, access to financial services, among others. In addition, inequality of opportunity is an important constraint. Social protection has an important role to play in protecting those living in vulnerable situations, and depending on the nature of that action, seeking to address the underlying causes of poverty and exclusion. Programs that direct resources to women, have shown greater impact on food security and other household-linked benefits. However, social and structural barriers may limit women's access to several types of social protection programs, including public works and agricultural input and support. In addition to these considerations, language, culture and tradition may influence willingness to participate and potential to benefit from social protection programs, unless national programs are adequately adapted to such sub-national contexts.

Few, if any, economic or social transformations over the past decades can be brought into focus without explicit attention being paid to the demographic transition, inextricably linked to several socio-cultural drivers. The growth of the urban sector, driven by both natural increase (fertility exceeding mortality) and rural-to-urban migration, helps to fuel agricultural transformation. The proportion of the population living in rural areas is declining in many countries, yet numbers are increasing in some, particularly in sub-Saharan Africa. Both fertility and mortality have been falling in rural areas, converging from levels higher than urban areas towards urban levels. Pressure and opportunity lead parts of growing rural cohorts to migrate to cities or seek diversified livelihoods within the rural sector. This raises concerns, particularly in sub-Saharan Africa where urban growth and the economic sectors are not in a position to cope with such a rapid transition and offer employment to rural dwellers as has occurred historically in other continents.

Predominantly male migration among youths and young adults over the course of the urban transition may have additional impacts on the gendered nature of economic roles and overall status of women. Increased urbanization means a growing gap between the location of food production and food consumption. It may also mean a change in lifestyle including dietary changes. As a result, there is a growing need for food processing, transportation, and transformation beyond the farm level, providing opportunities for jobs and entrepreneurship. In Ethiopia, Malawi, Mozambique, Tanzania, Uganda and Zambia, the transformation of the food system is forecast to add more jobs than any other sector of the economy by 2025. This is an opportunity to see that these jobs are accessible also to rural women and youth who may disproportionately live in vulnerable situations. Nonetheless, evidence suggests that women entrepreneurs face many additional barriers compared to their male counterparts including lack of mobility, access to finance, access to business networks and mentors, limited leadership experience, lower literacy and numeracy, discriminatory gender norms and stereotypes. Experience from other regions, also illustrates the risks to nutrition as dietary traditions are lost, and reliance on processed – often highly unhealthy food increases.

Today there are significant knowledge gaps on rural outmigration trends, which need to be tackled. This is particularly the case for migration driven by distress, when people do not perceive there is any other viable livelihood option except to migrate. Reliable data, disaggregated by sex, age, origin and destination are necessary to understand socio-economic conditions associated with migration. At the moment, these data are scarce.

Box 1: The unprecedented range of COVID-19 disruptions to the food system and livelihoods

The breadth and reach of the complex ramifications and disruptions from the COVID-19 pandemic are unprecedented. The impact from the pandemic parallels or exceeds the impact of major shocks over the past few decades, whether caused by natural disasters, disruption of financial and commodity markets, or conflict and civil strife. More challenging is the fact that, under Covid-19, all of these various shocks happen concurrently and engulf the entire globe, with no regions left untouched and thus poised to help fuel a possible recovery. There are therefore important lessons to be learned from the current pandemic to help shape more effective strategies to managing future shocks and their impact on the livelihood of the excluded and marginalized.

The Effects of Covid on marginalized communities: Income, poverty, and nutrition

Policies of social distancing and other measures adopted by governments to contain the spread of the pandemic have drastically affected food supply chains, with serious repercussions for the poor and vulnerable, particularly in LMICs. There is evidence that disruptions are more serious for the operation of informal market networks which dominate supply chains for traditional food staples that people living in poverty and situations of vulnerability depend on more heavily. Prices in these markets have reacted sharply to measures undertaken to control the pandemic. Moreover, higher food prices, the closing of informal markets and other disruptions to staple foods supply chains have been shown to impact on micronutrient intake and nutritional status of the poor. Finally, the effects of the pandemic on global commodity markets and trading systems are shown to have significant impact on economic growth and thus incomes and poverty levels, with likely disproportionate burden on the same vulnerable communities in both urban and rural areas. This is likely to worsen inequalities, food insecurity, and undernutrition including child wasting. COVID-19 therefore will likely have substantial implications for the achievement of the Sustainable Development Goals in LMICs, in particular SDG 2 (End hunger) and SDG 12 (Ensure sustainable consumption and production patterns).

Equity and policy responses to Covid and similar shocks

The Covid-19 crisis has particularly impacted already-marginalized segments of the population such as indigenous peoples, migrant workers, and informal sector employees. High vulnerability to changing economic conditions linked partly to a host of pre-existing barriers ranging from weak legal status, racism and lack of access to health, social security and education services all lead to disproportional impacts of the pandemic among the poor and disadvantaged.

Persistent and chronic vulnerability, a major manifestation of marginalization and exclusion, not only exacerbates the human cost of shocks, but it also complicates the search for effective responses. Resistance to confinement, curfews and other mitigation measures reported in the media across the world arise often from the considerable threat to livelihoods among the poorest and those living in situations of vulnerability. Successful strategies to deal with future shocks require having a better handle on equity and vulnerability before shocks strike.

Lessons for managing future shocks to protect livelihoods

Just like pre-existing conditions among humans raise the risk of serious consequences, chronic vulnerability patterns also raise the risk of exposure and extent of damage among excluded and marginalized communities in case of shocks such as Covid-19. Community vulnerability is determined by factors ranging from pre-existing levels of poverty, food insecurity, malnutrition, disease prevalence, poor health and education services to high population density.Investment in the capacity for good understanding of the patterns of vulnerability across various communities is therefore a major need for future preparedness, especially among LMIC.

For example, a report from the Indigenous Navigator, highlights the impact of Covid-19 on indigenous communities in 11 countries (Africa and Asia). On the one hand, the report identifies how pre-existing barriers in access to health, social security and education are fueling disproportional impacts of the pandemic on indigenous peoples. It also indicates a rise in food insecurity, related to loss of livelihoods and lack of access to land and natural resources. On the other hand, it underlines the central role played by communities in building the response and recovery to the global crisis resulting from the pandemic. The emphasis on Covid-19 response and recovery measures is that it needs to be respectful of the rights of indigenous peoples and support their livelihoods, economies, and resilience.

Equally important is a good understanding of the nature of operation of local food systems. Control measures that are not aligned with the basic features of food systems along complete value chains are certain to create second generation disruptions, with more serious impacts on livelihoods.

Finally, boosting preparedness capacities will require investment in a minimum infrastructure for real time data access and management. New development in remote sensing and machine learning offer real opportunities for better targeting and tracking in order to raise the effectiveness of response and mitigation measures to protect the poor and vulnerable.

Conclusions and implications for the development of game-changing solutions to enhance equitable livelihoods in food systems

The growth of the food systems presents enormous employment opportunities, but achievement of equitable livelihoods in food systems and resulting from changes in food systems will require that substantial progress be made to address the drivers of inequality. Food system transformation must also find the balance of food systems that favor and support healthy diets (i.e., those that minimize risk of both undernutrition and overweight and obesity), and do so in ways that are sustainable for the planet. We must transform not only the food system, but the structures and systems that continue to enable and exacerbate inequities. While we have reviewed and discussed the evidence related to drivers of inequitable livelihoods in relation with food system transformation within their respective categories, they are interconnected and progress to address one driver will likely require change across several. For example, globalization and trade interact with other powerful drivers, especially technology resource mobilization, and demographic trends, which shape food production, distribution and consumption.

We believe therefore, that enhancing equitable livelihoods will require solutions that:

1. **Are rights-based:** Solutions must recognize and hold stakeholders to account for human rights including living wage and the right to food, and advance the agenda towards the right to a healthy diet. Implications include not only a shift in policy and programmatic action, but increasing public pressure, and creating monitoring and accountability mechanisms that hold governments, businesses, and all stakeholders to account to uphold rights.
2. **Ensure long-term investment for structural changes:** Dismantling inequitable systems and structures that enable and exacerbate inequalities for food systems workers and consumers requires long-term investment, while achieving short term gains. Long-term vision should inform investment priorities in needed structural changes across the food system including those that will result in:
    - Dismantling barriers to expanded access to resources, technology, infrastructure and productive services among smallholders and other less powerful actors along the food system,
    - Policies and institutions that make sure that markets and trading regimes work for producers and consumers, including raising agricultural incomes and improving food access,
    - Regulatory and administrative arrangements and other instruments to ensure equitable access to productive assets.
3. **Directly inform local and national policy and programs:** Transformational change towards healthy, sustainable, and equitable food systems will require a breaking down of current policy silos in favor of coordinated policy agendas that permit the mapping and balancing of trade-off, benefits, and harms to human and planetary health. Including but not limited to agriculture, trade and food policies that simultaneously foster healthy diets, equitable opportunity and fair pay, and protect the environment, complemented with strengthened and well-targeted social protection.
4. **Enhance the development of and equitable deployment of contextually relevant innovation and technology:** The potential of innovation and technology to do good to human and planetary health is vast, but systems must be strengthened to ensure it does not exacerbate inequalities and that the balance of potential benefits and harms can be assessed. Research, development, and deployment of innovation and technology must meet the needs of smallholder producers and small businesses across the food value chains and of vulnerable consumers. Doing so requires enhanced processes and investments to develop such innovations and technologies drawing on all forms of scientific evidence and indigenous, local, and contextual knowledge.

In the following section we provide several general and more specific recommendations that can inform priorities for the game-changing solutions, bearing in mind the four criteria above. This list is not intended to be comprehensive, but rather to focus priorities that surface from the evidence review. Where feasible, we have included specific examples that illustrate the potential gains and pitfalls.

Alter power structures to enhance inclusive decision-making:

- At global and regional level, strengthen and enhance the existing institutional architecture to generate recommendations, good practice models, and technical support guidance for enhanced inclusive decision-making processes related to food systems within governments and organizations. Examples of key international organizations include FAO, IFAD, WFP, the World Bank Group, CGIAR, among others.
- Engage a coalition of local, regional, and international research institutions to generate and test a framework and parsimonious set of indicators that can be used to track progress towards inclusive decision-making processes and monitor livelihood improvements within international, national, regional, and local governments and organizations.
- Create or build on an existing accountability mechanism with mandate and resources to track progress towards and hold to account inclusive decision-making related to food systems transformations and their impacts within governments and organizations.

- Strengthen producer, vender, market and consumers organizations and other forms of collection action across the food system to enhance effective, non-tokenistic participation in decision-making processes related to rural and food systems transformation.
- Through all of these processes explore demographic, social, and cultural aspects that may influence participation in decision-making (e.g., gender, indigenous peoples, age), and ensure mechanisms are developed to address and track progress responsive to these unique contextual factors.
  - Dimitra Clubs seek to transform gender relations bringing women and men together to become more aware of gender inequalities in households and communities and working together to transform gender relations. Over 3,400 clubs existing reaching an estimated 2 million rural people. Examples of success include fighting malnutrition by challenging dietary taboos, reconciling long-standing political disputes, mobilizing to meet environmental challenges and establishing a credit cooperative to avoid debt.
  - The model of mutual accountability developed by the African Union as part of its Comprehensive African Agriculture Development Programme (CAADP) is an innovative and effective approach to promoting transparency, participation, and accountability for results. It involves two main components:
- Country-level joint sector reviews (JSRs) that allow governments, farmer organizations, private sector, civil society organizations and development partner organizations, at least once a year, to collectively review policy and program implementation performance as well as progress towards outcomes for the agricultural sector. The outcome is an action plan to deal with any major issues that emerge.
- The continental-level biennial review (BR) based on formally agreed target commitments related to agricultural sector investment, hunger and poverty, gender, youth, intra-African trade, and climate smart agriculture. Every two years, a report is prepared by each member state and submitted to the African Union Commission which uses it to rate each country on each of the target commitments. The report is submitted to Heads of State at their January Summit to debate the findings.

Protect the livelihoods of those living in situations of vulnerability, while creating opportunities:

- Expand the effective coverage of well-targeted social protection systems that uphold the livelihoods of those living in situations of vulnerability, using social protection instruments that can alleviate short term crises, but go beyond sheer poverty reduction to enhance opportunities to build assets and create wealth.
  - A promising model of boosting productivity and improving livelihoods through skills development, advisory services financial transfer is the FOMENTO model from Brazil. Research looking into the impact of its transfer to the African setting have provided solid evidence on its effectiveness to raise assets and increase earning potential of beneficiary farmers. This approach holds promise as a scalable approach to empowering and equipping the poor and those living in situations of vulnerability to integrate into the higher value segments of the food system value chains.
- Using existing or enhanced technology, develop and deploy better models to predict climate and other agricultural risks and use this data effectively to pre-empt and mitigate the impact of such risks on the production and livelihoods of small-scale agriculture and other producers in situations of vulnerability.
  - Climate Information Services (CIS) involve the production, translation (e.g., advisories, decision support), and communication and use of climate information. Appropriate information enables farmers to understand the role of climate vs. other drivers in perceived productivity changes and manage climate-related risks throughout the agricultural calendar. Econometric studies highlight CIS as one of the most important factors influencing adaptation and transformation of farming systems. For example, an analysis across more than 5,000 households in East and West Africa, South Asia, and Central America found access to CIS is a positive determinant of adaptation through agricultural diversification, and of agricultural intensification in Bangladesh and India.

Adapt institutions and policies to favor equitable food systems livelihoods:

- At global, national, sub-national and local level, develop and implement a cohesive set of policy actions that will enable sequential food systems transformations that favor the production, distribution, and consumption of nutritious over unhealthy foods, produced with territorial approaches that favor planetary health, and ensure equitable livelihoods for producers and wage earners across the food system.
  - Africa's Regional Economic Communities (RECs) are key actors working in collaboration with

the African Union (AU), in ensuring peace and stability in their regions. The RECs have been central to various transformative programs of the continent, including the New Partnership for Africa's Development (NEPAD) adopted in 2001. RECs have the immense challenge of working with governments, civil society, and the AU Commission in raising the standard of living of the people of Africa and contributing towards the progress and development of the continent through economic growth and social development.

- Adapt institutions and adopt policies that eliminate barriers in access to the fundamental services needed to enable those living in situations of vulnerability to take advantage of opportunities, ensuring, for example, the right to food, shelter, and health. Enhance more and better education investments that enable and empower youth as part of the productive rural and urban labor force.
  - The German dual training system for agricultural and horticultural professions is a good model for an institutional infrastructure that creates a path to good paying jobs and better livelihoods. It is a country wide system that offers a mixture of practical, multi-year on the job training of apprentices by "master-farmers," ongoing theoretical training for active and aspiring farmers, as well as modular, usually short term courses on specific skills and good practices.
- Adapt institutions and adopt policies that eliminate barriers in access to the natural (e.g., land, water, forests), economic (e.g., credit, business planning), and technological resources (e.g., digital, appropriate modern biotechnology) needed to enhance and ensure equitable livelihoods for producers and SMEs across the food value chain. Such policy and institutional arrangements should explicitly favor those who have been traditionally excluded, particularly women, youth, and indigenous peoples.
  - The Land Matrix Initiative is an independent global land monitoring initiative made up of a number of global and regional partners, originally established in 2009 to address the lack of robust data on large scale land acquisitions and investments. The initiative now covers almost 100 countries. It captures intended and failed attempts to acquire land through purchase, lease or concession and demonstrates the complexity and political dimension of land acquisition.
- Enhance the effectiveness of international organizations to facilitate global trade arrangements that promote and protect livelihoods and the right to food. An enhanced role of the World Trade Organization is particularly salient.

Increase investment to realize the potential of improved institutional and policy actions:

- More coordination among government entities would internalize externalities across sectors and address trade-offs such as to deliver the most impactful and site adapted interventions for the poor and those living in vulnerable situations. Increasing investment in public infrastructure (e.g., roads, markets, irrigation, etc.) also helps to enhance the livability of communities, while favoring the production, sale, and consumption of nutritious food.
- Expand and use innovative financial mechanisms (e.g., impact investment) for small and medium-sized farmers and businesses along the food value chains to expand and intensify their production, and improve safety, quality, and sustainability, prioritizing nutritious over unhealthy foods.
  - Two models to nurture and support the development of the emerging processing processor and other segments of food system value chain to boost profits and employment for low skilled workers. The first, with well-documented impact, is the model of Cluster based industrialization which provide a critical mass of infrastructure, services, and networking opportunities. The second is the Kaizen model from Japan, which has been recently tested in Africa with promising results.

Hold governments, businesses, and organizations to account for ensuring equitable livelihoods:

- Engage a coalition of local, regional, and international research institutions to generate and test a framework and parsimonious set of indicators and metrics that can be used to track progress towards equitable livelihoods within business, international, national, regional, and local governments, and organizations.
- Create or build on an existing accountability mechanism with mandate and resources to track progress towards and hold to account equitable livelihoods in food systems across all businesses, governments, and organizations, ensuring data can and are presented disaggregated for women, youth, indigenous peoples, migrant workers, and others as appropriate.

Realize the potential of science, innovation, technology, and evidence to favor equitable livelihoods:

- Apply advances in bioscience innovations, including genetic engineering, genome editing, as well as soil, plant and animal husbandry and health technologies and practices for a successful transformation of food systems. Meeting food systems challenges related to raising production, improving efficiency and saving and restoring production resources in the face of a changing climate will require that benefits from advances in these areas are broad based and inclusive of the poor and marginalized actors in food systems value chains. This in turn will require investing in adapting technology advances to local conditions for greater accessibility and affordability to, as well as safe utilization, by smallholder farmers.

- Develop and deploy digital innovations to advance efficiency and inclusiveness of food systems. Digital services platform from eCommerce to financial and technology support services help link farmers and rural communities to actors and service providers in domestic and global value chains. Lower income countries can also overcome at lower cost and in a shorter period of time a number institutional, infrastructural and financial obstacles to transforming food systems through strategic deployment of remote sensing, big data, machine learning, artificial intelligence, robotics, drones and digital technologies for more efficient cropping systems.
- Improve the availability, quality, accessibility, and use of data that can map and inform actions to reduce inequalities in the food systems.
  - The newly developed food systems dashboard is an important advance in this regard. The dashboard consolidates existing data from multiple sources, provides useful tools to visualize and understand the data, and are developing a set of diagnostics that will permit the identification of potential policy and program priorities. That said, many data gaps, particularly at national and sub-national level and the full potential of such tools will be realized only once such data gaps are filled.
- Assess deployment pathways (e.g., extension services, farmer schools, etc.), and potential for those traditionally excluded (e.g., women, youth, small holders, indigenous peoples) to benefit when setting priorities for and making investment decisions related to the development of innovations and new technologies for food systems.
  - For example, new technologies are being used to very positive effect to ensure that nutrition does not “exit” the food supply chain. Improving traditional products and processes by reengineering the unit operations can be an efficient way to both generate rural employment in SMEs and incomes for family farmers and increase the safety and nutritional quality of foods while maintaining or improving the organoleptic characteristics of traditional products. Nonetheless, evaluation has also shown that several “good ideas” may have harmful side effects when a comprehensive approach to understanding all different pathways leading from agricultural interventions towards the nutrition of individuals is insufficiently considered.
- Develop and use creative approaches to learn, build on, and document indigenous knowledge related to food production, processing, consumption, and natural resource management in ways that such knowledge can be shared, adapted, and adopted and tested in new contexts if appropriate, and drawn on in the establishment of recommendations, guidance, and good practice. New approaches are instrumental to revitalize indigenous food systems and produce, process, and consume food in culturally relevant and ecologically sustainable ways.
  - Several examples exist illustrating the potential and power of mobilizing available indigenous knowledge for the establishment of policy recommendations, guidance, and good practice.
  - With the threat of climate change and the need to adapt to its adverse effects, indigenous peoples’ communities are proving to be an important source of climate history and baseline data and are already playing a valuable role by providing local-scale expertise, monitoring impacts, and implementing adaptive responses at the local level. For example, on-farm conservation of crops is a dynamic process, in which varieties managed by indigenous farmers continue to evolve in response to natural and human selection, leading to crops with better adaptive potential. For instance, “kreb” is a mixture of wild and cultivated species (such as Digitaria exilis or “fonio”) which is traditionally used in the Sahel by pastoralists. The latter harvest these seeds from the open grasslands and manage the wild species to ensure sustainable seed production for human consumption and fodder.
  - Rapid dietary change of indigenous peoples worldwide is posing threats to the use of traditional food and the traditional knowledge required for the traditional food system maintenance. Several foods and combinations have illustrated potential to decrease risk of micronutrient deficiencies. Such traditions may be fundamental for slowing the nutrition transition and accompanying increasing preventable diet-related non-communicable diseases

REFERENCES:

1. HLPE. Food security and nutrition: building a global narrative towards 2030. A report by the High Level Panel of Experts on Food Security and Nutrition of the committee on World Food Security. 2020.
2. Dury S, Bocoum I. Le « paradoxe » de Sikasso (Mali) : pourquoi « produire plus » ne suffit-il pas pour bien nourrir les enfants des familles d'agriculteurs ? 1 2012; 21: 324-336 (1).
3. HLPE. Nutrition and Food Systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, 2017.
4. von Braun J, Afsana K, Fresco L, Hassan M, Terero M. Food systems - Definition, Concept and Application for the UN Food Systems Summit. A paper from the Scientific Group of the UN Food Sysetms Summit. 2021 https://sc-fss2021.org/wp-content/uploads/2021/03/ScGroup_Food_Systems_paper_March-5-2021.pdf (accessed March 9, 2021).
5. Cotula L, Food and Agriculture Organization of the United Nations. The right to food and access to natural resources using human rights arguments and mechanisms to improve resource access for the rural poor. Rome: FAO, 2008.
6. IPCC. Special Report on Climate Change and Land. An IPCC special report on climate change, desertification, land degradation, sustainable land managmenet, food security, and greenhouse has fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change, 2020.
7. Sandrasekaran M, Kasthuri T, Singh Khola O. Soil and water conservation in India: Strategies and research challenges-Indian Journals. Journal of Soil and Water Conservation 2017; 16: 312–9.
8. OECD. Rural Well-being: Geography of Opportunities. Paris: OECD Publishing, 2020 https://doi.org/10.1787/d25cef80-en.
9. IPCC. Sixth Assessment Report — IPCC. https://www.ipcc.ch/assessment-report/ar6/ (accessed March 14, 2021).
10. O'Neal M, Nearing M, Vining R, Southworth J, Pfeifer R. Climate change impacts on soil erosion in Midwest United States with changes in crop management. CATENA 2005; 61: 165–84.
11. Boardman J, Poesen J. Soil Erosion in Europe: Major Processes, Causes and Consequences. In: Soil Erosion in Europe. John Wiley & Sons, Ltd, 2006: 477–87.
12. Borrelli P, Robinson DA, Fleischer LR, et al. An assessment of the global impact of 21st century land use change on soil erosion. Nat Commun 2017; 8: 1–13.
13. Molden D, Burton M, Bos MG. Performance assessment, irrigation service delivery and poverty reduction: benefits of improved system management. Irrigation and Drainage 2007; 56: 307–20.
14. Falkenmark M. Meeting water requirements of an expanding world population. Philosophical Transactions of the Royal Society of London Series B: Biological Sciences 1997; published online July 29. DOI:10.1098/rstb.1997.0072.
15. Sullivan C, Meigh J. Considering the Water Poverty Index in the context of poverty alleviation. Water Policy 2003; 5: 513–28.
16. Rogers V, Meara P, Barnett-Legh T, Curry C, Davie E. Examining the LLAMA aptitude tests. Journal of the European Second Language Association 2017; 1: 49–60.
17. Bindoff NL, Cheung WWL, Kairo JG, et al. Changing Ocean, Marine Ecosystems, and Dependent Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. 2019.
18. FAO. Impacts of climate change on fisheries and aquaculture. Synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper 627. 2018.
19. Scholze M, Knorr W, Arnell NW, Prentice IC. A climate-change risk analysis for world ecosystems. PNAS 2006; 103: 13116–20.
20. Munasinghe M. Development, Equity and Sustainability (DES) in the Context of Climate Change. In: Pichs R, Swart R, Leary N, Ormond F, eds. Development, Sustainability and Equity. Geneva: Intergovernmental Panel on Climate Change, 2020.
21. HLPE. Food losses and waste in the context of sustainable food systems. A report by the High Level panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, 2014.
22. ACAPS. Famine: Northeast Nigeria, Somalia, South Sudan, and Yemen. 2017 https://reliefweb.int/sites/reliefweb.int/files/resources/20170522_acaps_famine_theme_final_report.pdf (accessed Nov 29, 2020).
23. Pingali PL. Green Revolution: Impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences of the United States of America 2012; 109: 12302.
24. Hueston W, McLeod A. Overview of the global food system: Changes over time/space and lessons for future food security. In: Improving Food Safety Through a One Health Approach: Workshop Summary. Washington, DC: National Academies Press (US), 2012.
25. Latour B. Science in Action: How to Follow Scientists and Engineers Through Society. Boston: Harvard University Press, 1987.

26. HLPE. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, 2019.
27. Mascarenhas M, Busch L. Seeds of Change: Intellectual Property Rights, Genetically Modified Soybeans and Seed Saving in the United States. Sociologia Ruralis 2006; 46: 122–38.
28. World Bank. World Development Report 2008. Washington, DC, 2007 DOI:10.1596/978-0-8213-6807-7.
29. Glenna LL, Cahoy DR. Agribusiness Concentration, Intellectual Property, and the Prospects for Rural Economic Benefits from the Emerging Biofuel Economy. Southern Rural Sociology 2009; 24: 111–29.
30. Heinemann JA, Massaro M, Coray DS, Agapito-Tenfen SZ, Wen JD. Sustainability and innovation in staple crop production in the US Midwest. International Journal of Agricultural Sustainability 2014; 12: 71–88.
31. HarvestPlus. Catalyzing Biofortified Food Systems: 2018 Annual Report. Washington, DC: HarvestPlus, 2018 https://www.harvestplus.org/sites/default/files/publications/153613_HarvestPlus_AR_2018_Proof.pdf (accessed March 9, 2021).
32. McMullin S, Njogu K, Wekesa B, et al. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: a new approach for providing year-round micronutrients to smallholder farmers. Food Sec 2019; 11: 1355–72.
33. Areal FJ, Riesgo L, Rodríguez-Cerezo E. Economic and agronomic impact of commercialized GM crops: a meta-analysis. The Journal of Agricultural Science 2013; 151: 7–33.
34. Huang J, Rozelle S, Pray C, Wang Q. Plant Biotechnology in China. Science 2002; 295: 674–6.
35. Kathage J, Qaim M. Economic impacts and impact dynamics of Bt (Bacillus thuringiensis) cotton in India. PNAS 2012; 109: 11652–6.
36. Qiao F, Huang J, Wang X. Fifteen Years of Bt Cotton in China: Results from Household Surveys. World Development 2017; 98: 351–9.
37. Vognan G, Fok M. Performance différenciée du coton Bt en début de diffusion : cas du Burkina Faso. Cah Agric 2019; 28: 26.
38. Kloppenburg J. Impeding Dispossession, Enabling Repossession: Biological Open Source and the Recovery of Seed Sovereignty. Journal of Agrarian Change 2010; 10: 367–88.
39. Bonny S. Corporate Concentration and Technological Change in the Global Seed Industry. Sustainability 2017; 9: 1632.
40. Dinesh D, Campbell BM, Bonilla-Findji O, Richards M. 10 best get innovations for adaptation in agriculture: A supplement to the UNFCCC NAP Technical Guidelines. Wageningen, The Netherlands: CGIAR Research Program on Climate change, Agriculture and Food Security (CCAFS), 2017 www.ccafs.cgiar.org.
41. Pew Research Center. Smartphone Ownership and Internet Usage Continues to Climb in Emerging Economies. 2016 https://www.pewresearch.org/global/2016/02/22/smartphone-ownership-and-internet-usage-continues-to-climb-in-emerging-economies/.
42. Qiang CZ, Kuek SC, Dymond A, Esselaar S. Mobile Applications for Agriculture and Rural Development. Washington, DC: ICT Sector Unit, World Bank, 2012.
43. World Bank. World Development Report 2016: Digital Dividends | World Development Report. 2016.
44. Deichmann U, Goyal A, Mishra D. Will digital technologies transform agriculture in developing countries? Agricultural Economics 2016; 47: 21–33.
45. 45 Salemink K, Strijker D, Bosworth G. Rural development in the digital age: A systematic literature review on unequal ICT availability, adoption, and use in rural areas. Journal of Rural Studies 2017; 54: 360–71.
46. OECD. Innovation, Productivity and Sustainability in Food and Agriculture: Main Findings from Country Reviews and Policy Lessons, OECD Food and Agricultural Reviews. Paris: OECD Publishing, 2019 https://doi.org/10.1787/c9c4ec1d-en.
47. Vesper I. Evidence patchy on value of mobile apps for farmers. SciDev.Net. https://www.scidev.net/global/news/evidence-patchy-on-value-of-mobile-apps-for-farmers/ (accessed March 9, 2021).
48. Baumüller H. The Little We Know: An Exploratory Literature Review on the Utility of Mobile Phone-Enabled Services for Smallholder Farmers. Journal of International Development 2018; 30: 134–54.
49. Samberg L. How new technology could help to strengthen global good security. World Economic Forum. https://www.weforum.org/agenda/2018/03/food-security-s-social-network/ (accessed March 15, 2021).
50. International Monetary Fund. Fiscal Policy and Income Inequality. Policy Papers 2014; 14. DOI:10.5089/9781498343671.007.
51. Rodríguez-Pose A, Ezcurra R. Is fiscal decentralization harmful for economic growth? Evidence from the OECD countries. J Econ Geogr 2011; 11: 619–43.
52. OECD. Global value chains in agriculture and food: A synthesis of OECD analysis. OECD Publishing, 2020.

53. OECD. Linking Indigenous Communities with Regional Development. Paris: OECD Publishing, 2019 https://doi.org/10.1787/3203c082-en.
54. HLPE. Social protection for food security. A report of the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, 2012.
55. Putnam P. Bowling Alone: The Collapse and Revival of American Community. New York, NY: Simon & Schuster Paperbacks, 2000.
56. Bourguignon F, Dessus S. Equity and Development: Political Economy Considerations. 2009.
57. Lowder SK, Bertini R, Karfakis P, Croppenstedt A. Transformation in the size and distribution of farmland operated by household and other farms in select countries of sub-Saharan Africa. 2016 Fifth International Conference, September 23-26, 2016, Addis Ababa, Ethiopia 2016; published online Sept. https://ideas.repec.org/p/ags/aaae16/246969.html (accessed Oct 25, 2020).
58. Pryck JD de, Termine P. Gender Inequalities in Rural Labor Markets. Gender in Agriculture 2014; : 343–70.
59. Food and Agriculture Organization of the United Nations, editor. The future of food and agriculture: trends and challenges. Rome: Food and Agriculture Organization of the United Nations, 2017.
60. Jayne T, Chamberlin J, Headey D. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. Food Policy 2014; 48: 1–17.
61. Vandergeten E, Azadi H, Teklemariam D, Nyssen J, Witlox F, Vanhaute E. Agricultural outsourcing or land grabbing: a meta-analysis. Landscape Ecol 2016; 31: 1395–417.
62. King R. Land Reform: A World Survey. Routledge, 1977.
63. Greenville J, Kawasaki K, Jouanjean M-A. Dynamic Changes and Effects of Agro-Food GVCS. Paris: OECD Publishing, 2019 DOI:10.1787/43b7bcec-en.
64. Greenville J, Kawasaki K, Flaig D, Carrico C. Influencing GVCs through Agro-Food Policy and Reform. Paris: OECD Publishing, 2019 https://doi.org/10.1787/9ce888e0-en.
65. Feenstra RC, Hanson GH. Globalization, Outsourcing, and Wage Inequality. National Bureau of Economic Research, 1996 DOI:10.3386/w5424.
66. Feenstra RC, Hanson GH. Global Production Sharing and Rising Inequality: A Survey of Trade and Wages. In: Handbook of International Trade. John Wiley & Sons, Ltd, 2008: 146–85.
67. González H. Specialization on a global scale and agrifood vulnerability: 30 years of export agriculture in Mexico. Development Studies Research An Open Access Journal 2014; published online Oct 15. https://www.tandfonline.com/doi/abs/10.1080/21665095.2014.929973 (accessed March 16, 2021).
68. Oya C. Contract Farming in Sub-Saharan Africa: A Survey of Approaches, Debates and Issues. Journal of Agrarian Change 2012; 12: 1–33.
69. Badiane O, Odjo S. Regional Trade and Volatility in Staple Food Markets in Africa. In: Food Price Volatility and Its Implications for Food Security and Policy. Springer Open, 2016: 385–412.
70. Reardon. Transformation of African Agrifood Systems in the New Era of Rapid Urbanization and the Emergence of a Middle Class. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/130005 (accessed Oct 25, 2020).
71. Bouët A, Odjo SP, Zaki C. Africa agriculture trade monitor 2020. Washington, DC: International Food Policy Research Institute, 2020 DOI:10.2499/9780896293908.
72. Tschirley DL, Snyder J, Dolislager M, et al. Africa ’ s unfolding diet transformation: implications for agrifood system employment. Journal of Agribusiness in Developing and Emerging Economies 2015; 5: 102–36.
73. Dutt P, Mitra D. Inequality and the Instability of Polity and Policy*. The Economic Journal 2008; 118: 1285–314.
74. Alesina. Income distribution, political instability, and investment. European Economic Review 1996; 40: 1203–28.
75. Acemoglu D, Robinson JA. The Political Economy of the Kuznets Curve. Review of Development Economics 2002; 6: 183–203.
76. Losch B, Freguin-Gresh S, White ET. Structural Transformation and Rural Change Revisited - Challenges for Late Developing Countries in a Globalizing World. Washington, DC: World Bank, 2012.
77. Independent Evaluation Group (IEG). The World Bank Group and the Global Food Crisis: An Evaluation of the World Bank Group Response. Washington, DC: The World Bank, 2014 DOI:10.1596/978-1-4648-0091-7.
78. IMF. International Monetary Fund Annual Report 2015. Washington, DC: International Monetary Fund, 2015.
79. UNDESA World Social Report | DISD. https://www.un.org/development/desa/dspd/world-social-report.html (accessed Oct 25, 2020).
80. Ulimwengu J, Badiane O. Vocational Training and Agricultural Productivity: Evidence from Rice Production in Vietnam. Journal of Agricultural Education and Extension 2010; 16: 399–411.
81. Badiane O, Ulimwengu JM. Malaria incidence and agricultural efficiency in Uganda. 2013. DOI:10.1111/j.1574-0862.2012.00626.x.

82. Wouterse F, Badiane O. The role of health, experience, and educational attainment in agricultural production: Evidence from smallholders in Burkina Faso. Agricultural Economics 2019; 50: 421–34.
83. Allen S, Badiane O, Sene L, Ulimwengu J. Government Expenditures, Health Outcomes and Marginal Productivity of Agricultural Inputs: The Case of Tanzania. Journal of Agricultural Economics 2014; 65: 637–62.
84. Quisumbing AR, Meinzen-Dick RS, Njuki J. 2019 Annual trends and outlook report: Gender equality in rural Africa: From commitments to outcomes. 2019. DOI:10.2499/9780896293649.
85. Knippenberg E, Hoddinott J. Shocks, social protection, and resilience: Evidence from Ethiopia. Ethiopia: IFPRI, Ethiopian Development Research Institute (EDRI), 2017.
86. International Fund for Agricultural Development. Rural development: report 2016 : fostering inclusive rural transformation. Roma: IFAD, 2016.
87. Research Institute (IFPRI) IFP. 2019 Global food policy report. Washington, DC: International Food Policy Research Institute, 2019 DOI:10.2499/9780896293502.
88. FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World 2020. Rome: FAO, 2020 DOI:10.4060/ca9692en.
89. Batal M, Decelles S. A Scoping Review of Obesity among Indigenous Peoples in Canada. Journal of Obesity 2019; 2019. DOI:10.1155/2019/9741090.
90. Domingo A, Spiegel J, Guhn M, et al. Predictors of household food insecurity and relationship with obesity in First Nations communities in British Columbia, Manitoba, Alberta and Ontario. Public Health Nutrition 2020; : 1–13.
91. Valeggia CR, Snodgrass JJ. Health of Indigenous Peoples. Annual Review of Anthropology 2015; 44: 117–35.
92. Stephens C, Nettleton C, Porter J, Willis R, Clark S. Indigenous peoples' health—why are they behind everyone, everywhere? The Lancet 2005; 366: 10–3.
93. Desmarais AA, Wittman H. Farmers, foodies and First Nations: getting to food sovereignty in Canada. Journal of Peasant Studies 2014; 41: 1153–73.
94. Vernon RV. A Native Perspective: Food Is More Than Consumption. 1 2015; 5: 137–42.
95. Mosby I, Galloway T. "Hunger was never absent": How residential school diets shaped current patterns of diabetes among Indigenous peoples in Canada. CMAJ 2017; 189: E1043–5.
96. Levy S. Progress against poverty: sustaining Mexico's Progresa-Oportunidades program. Washington, D.C: Brookings Institution Press, 2006.
97. Théodore FL, Bonvecchio Arenas A, García-Guerra A, et al. Sociocultural Influences on Poor Nutrition and Program Utilization of Mexico's Conditional Cash Transfer Program. J Nutr 2019; 149: 2290S-2301S.
98. Dyson T. The Role of the Demographic Transition in the Process of Urbanization on JSTOR. Population and Development Review, Population Council 2011; 37: 34–54.
99. United Nations, editor. Replacement migration: is it a solution to declining and ageing populations? New York: United Nations, 2001.
100. Lastarria-Cornhiel S. Feminization of Agriculture: Trends and Driving Forces. Background paper for the World Development Report. Washington, DC, 2008.
101. Gray C. Environment, Land, and Rural Out-migration in the Southern Ecuadorian Andes. World Development 2009; 37: 457–68.
102. Gustafson S. The Global Food System and Employment | Food Security Portal. 2018; published online Feb 13. https://www.foodsecurityportal.org/blog/global-food-system-and-employment (accessed March 14, 2021).
103. Nordhagen S, Condes S. Supporting gender-equitable food systems through access to finance for small- and medium-sized companies. Geneva, Switzerland: Global Alliance for Improved Nutrition (GAIN), 2020.
104. Popkin BM, Reardon T. Obesity and the food system transformation in Latin America. Obesity Reviews 2018; 19: 1028–64.
105. Carletto G, Ruel M, Winters P, Zezza A. Farm-Level Pathways to Improved Nutritional Status: Introduction to the Special Issue. The Journal of Development Studies 2015; 51: 945–57.
106. Bron GM, Siebenga JJ, Fresco LO. In the age of pandemics, connection food systems and health: a Global One Health approach. Food Systems Summit Brief prepared by Research Parners of the Scientific Group of the Food Systems Summit. 2021.
107. Badiane O, Collins J. AKADEMIYA2063's Multi-Workstream Agenda on Covid-19. AKADEMIYA2063 Covid-19 Bulletin No. 1, July. Kigali: AKADEMIYA2063, 2020.
108. Hobbs JE. Food supply chains during the COVID-19 pandemic. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 2020; 68: 171–6.
109. Barrett CB. Actions now can curb food systems fallout from COVID-19. Nat Food 2020; 1: 319–20.
110. OECD. Food Supply Chains and COVID-19: Impacts and Policy Lessons. 2020 http://www.oecd.org/coronavirus (accessed March 9, 2021).

111. Fei S, Ni J, Santini G. Local food systems and COVID-19: an insight from China. Resources, Conservation and Recycling 2020; 162: 105022.
112. Hatab AA, Lagerkvist C-J, Esmat A. Risk perception and determinants in small- and medium-sized agri-food enterprises amidst the COVID-19 pandemic: Evidence from Egypt. Agribusiness 2021; 37: 187–212.
113. Resnick D. 16. COVID-19 lockdowns threaten Africa's vital informal urban food trade. ; : 2.
114. Matchaya G, Nhlengethwa S, Fakudze B, Greffiths J. Maize Grain Price trends in food surplus and deficit areas of Mozambique under Covid-19. Covid-19 Bulletin No. 7, September. Kigali: AKADEMIYA2063, 2020.
115. Guthiga P, Kirui L, Karugia J. The impact of the COVID-19 pandemic on staples food prices in local markets: The case of cooking banana ('Matooke') in Uganda. Covid-19 Bulletin No. 12, October. Kigali: AKADEMIYA2063, 2020.
116. Ulimwengu J, Magne-Domgho L. Impact of COVID-19 on hidden hunger in Senegal. Covid-19 Bulletin No. 8, August. Kigali: AKADEMIYA2063, 2020.
117. Fofana I, Sall LM. Impact of trade shocks on growth and poverty in selected countries. Covid-19 Bulletin No. 13, November. Kigali: AKADEMIYA2063, 2020.
118. Headey D, Heidkamp R, Osendarp S, et al. Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. The Lancet 2020; 396: 519–21.
119. Jribi S, Ismail HB, Doggui D, Debbabi H. COVID-19 virus outbreak lockdown: What impacts on household food wastage? Environ Dev Sustain 2020; 22: 3939–55.
120. Gamlen A. Migration and mobility after the 2020 pandemic: The end of an age? Geneva: International Organization for Migration (IOM), 2020.
121. International Labour Organization. Protecting migrant workers during the COVID-19 pandemic. Recommendations for policy-makers and Constituents. 2020.
122. Marschke M, Vandergeest P, Havice E, et al. COVID-19, instability and migrant fish workers in Asia. Maritime Studies 2021; 20: 87–99.
123. Ulimwengu JM, Collins J. Assessing community vulnerability to Covid-19 in the Sahel Covid-19 Bulletin No. 10, October. Kigali: AKADEMIYA2063, 2020.
124. IWGIA, ILO. The impact of COVID-19 on indigenous communities: Insights from the Indigenous Navigator. The International Working Grioup for Indigenous Affairs, and the International Labour Organization, 2020.
125. Liverpool-Tasie LSO, Reardon T, Belton B. "Essential non-essentials": COVID-19 policy missteps in Nigeria rooted in persistent myths about African food supply chains. Applied Economic Perspectives and Policy 2021; 43: 205–24.
126. Ly R, Dia K, Diallo M, Ahid M, Ceesay B. 2020 Pearl millet production forecasts for selected West African countries: Côte d'Ivoire, Mali, Burkina Faso, Sierra Leone, The Gambia, and Senegal. Covid-19 Bulletin No. 14, December. Kigali: AKADEMIYA2063, 2020.
127. Neufeld LM, Hendriks S, Hugas M. Healthy diet: A definition for the United Nations Food Systems Summit. 2021.
128. UN. Universal Declaration of Human Rights. 1948 https://www.ohchr.org/EN/UDHR/Documents/UDHR_Translations/eng.pdf.
129. FAO. Dimitra project: Gender, rural women and development. http://www.fao.org/dimitra/about-dimitra/en/ (accessed March 20, 2021).
130. Ulimwengu JM, Matchaya G, Makombe T, Oehmke JF. Mutual accountability in African agricultural transformation. In: Resnick D, Diao X, Tadesse G, eds. Resakss Annual Trends and Outlook Report, 0 edn. Washington, DC and Kigali: International Food Policy Research Institute (IFPRI) and AKADEMIYA2063, 2020: 182–94.
131. Ambler K, de Brauw A, Godlonton S. Agriculture support services in Malawi: Direct effects, complementarities, and time dynamics. Washington, DC: International Food Policy Research Institute (IFPRI), 2018 DOI:10.2499/1037800842.
132. Loboguerrero AM, Campbell BM, Cooper PJM, Hansen JW, Rosenstock T, Wollenberg E. Food and Earth Systems: Priorities for Climate Change Adaptation and Mitigation for Agriculture and Food Systems. Sustainability 2019; 11: 1372.
133. Caron P, Valette E, Wassenaar T, Coppens G, d'Eeckenbrugge G, Papazian V. Living territories to transform the world. Paris: Quae, 2017 DOI: 10.35690/978-2-7592-2731-0.
134. Adepoju A. Fostering Free Movement of Persons in West Africa: Achievements, Constraints, and Prospects for Intraregional Migration. International Migration 2002; 40: 3–28.
135. Office of the Special Adviser on Africa (OSAA). https://www.un.org/en/africa/osaa/ (accessed March 22, 2021).
136. UNICEF. Every Child Learns. UNICEF Education Strategy 2019-2030. New York, NY: UNICEF, 2019.
137. Menashe-Oren A, Stecklov G. Rural/Urban Population Age and Sex Composition in sub-Saharan Africa 1980–2015. Population and Development Review 2018; 44: 7–35.
138. Thiele H. Deula: Presentation of our Institution. https://www.deula.de/fileadmin/Redakteure/Witzenhausen/Presentation_institution.pdf (accessed March 22, 2021).

139. FAO. Developing gender-equitable legal frameworks for land tenure. A legal assessment tool. FAO, 2016.
140. Land Matrix. https://landmatrix.org/ (accessed March 22, 2021).
141. Badiane O, Makombe T. Beyond a middle income Africa: Transforming African economies for sustained growth with rising employment and incomes. 2015. DOI:10.2499/9780896298927.
142. De Pinto A, Ulimwengu JM. A thriving agricultural sector in a changing climate: Meeting Malabo Declaration goals through climate-smart agriculture. 2017. DOI:10.2499/9780896292949.
143. Boosting growth to end hunger by 2025: The role of social protection. ReSAKSS Annual Trends and Outlook Report 2017-2018. Washington, D.C: IFPRI, 2018 DOI:10.2499/9780896295988.
144. Sonobe T, Otsuka K. Cluster-Based Industrial Development. A Comparative Study of Asia and Africa. United Kingdom: Palgrave Macmillan, 2011 DOI: 10.1057/9780230295124.
145. Sonobe T, Jin K, Otsuka K. Applying the Kaizen in Africa. Saint Philip Street Press, 2020.
146. Food Systems Dashboard - Diets and Nutrition. Food Systems Dashboard. https://foodsystems-dashboard.org/ (accessed March 22, 2021).
147. Fanzo J, Haddad L, McLaren R, et al. The Food Systems Dashboard is a new tool to inform better food policy. Nat Food 2020; 1: 243–6.
148. Fanzo JC, Downs S, Marshall QE, Pee S de, Bloem MW. Value Chain Focus on Food and Nutrition Security. In: de Pee S, Taren D, Bloem M, eds. Nutrition and Health in a Developing World. Humana Press, Cham., 2017: 753–70.
149. Obodai M, Uduro-Yeboah C, Amoa-Awua W, et al. Kenkey production, vending, and consumption practices in Ghana. Food Chain 2015; 4: 275–88.
150. Pintado A, Monteiro M, Talon R, et al. Consumer acceptance and sensory profiling of reengineered kitoza products. Food Chemistry 2016; 198: 75–84.
151. Dury S, Alpha A, Bichard A. The Negative Side of the Agricultural-Nutrition Impact Pathways: A Literature Review. World Food Policy 2015; 2: 78–100.
152. Lugo-Morin DR. Indigenous communities and their food systems: a contribution to the current debate. J Ethn Food 2020; 7: 6.
153. Blanchet R, Willows N, Johnson S, Salmon Reintroduction Initiatives O, Batal M. Traditional Food, Health, and Diet Quality in Syilx Okanagan Adults in British Columbia, Canada. Nutrients 2020; 12. DOI:10.3390/nu12040927.
154. Okanagan Nation Alliance – ałi kwu_swiwi-numtax, ałi kwu_suknaqinx, ałi axa/ L/tmxwula/xw. https://www.syilx.org/ (accessed March 22, 2021).
155. Cree Hunters and Trappers Income Security Board. http://www.chtisb.ca/program/ (accessed March 22, 2021).
156. Sherwood S. Strengthening impact of the healthy food consumption campaign : 250,000 families in Ecuador. 2019 https://idl-bnc-idrc.dspacedirect.org/handle/10625/59373.
157. Grey S, Patel R. Food sovereignty as decolonization: some contributions from Indigenous movements to food system and development politics. Agriculture and Human Values 2014; 32: 431–44.
158. Mabhaudhi T, Chibarabada TP, Chimonyo VGP, et al. Mainstreaming Underutilized Indigenous and Traditional Crops into Food Systems: A South African Perspective. Sustainability 2018; 11: 1–22.
159. Kurashima N, Fortini L, Ticktin T. The potential of indigenous agricultural food production under climate change in Hawai'i. Nature Sustainability 2019; 2: 191–9.
160. Asogwa I s, Okoye J i, Oni K. Promotion of Indigenous Food Preservation and Processing Knowledge and the Challenge of Food Security in Africa. Journal of Food Security 2017; 5: 75–87.
161. Ministerio de Salud Pública del Ecuador, FAO. Guías Alimentarias del Ecuador. Quito, Ecuador: FAO, 2021 DOI:10.4060/ca9928es.
162. Sherwood S, Arce A, Paredes M, editors. Food, Agriculture and Social Change. The Everyday Vitality of Latin America. London, UK: Routledge, 2017 https://doi.org/10.4324/9781315440088.
163. Deaconu A, Mercille G, Batal M. The Agroecological Farmer's Pathways from Agriculture to Nutrition: A Practice-Based Case from Ecuador's Highlands. Ecology of food and nutrition 2019; 58: 142–65.
164. Chianese F. The Traditional Knowledge Advantage: Indigenous peoples' knowledge in climate change adaptation and mitigation strategies. Rome: IFAD.
165. Kuhnlein HV, Receveur O. Dietary Change and Traditional Food Systems of Indigenous Peoples. Annual Review of Nutrition 1996; 16: 417–42.
166. Kuhnlein HV. Karat, Pulque, and Gac: Three Shining Stars in the Traditional Food Galaxy. Nutr Rev 2004; 62: 439–42.

This Report was prepared by members of the Scientific Group.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
IFPRI

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

A REVIEW OF EVIDENCE ON GENDER EQUALITY, WOMEN'S EMPOWERMENT, AND FOOD SYSTEMS

by Jemimah Njuki, Sarah Eissler, Hazel Malapit , Ruth Meinzen-Dick,
Elizabeth Bryan and Agnes Quisumbing

ABSTRACT

Achieving gender equality and women's empowerment in food systems can result in greater food security and better nutrition, and more just, resilient, and sustainable food systems for all. This paper uses a scoping review to assess the current evidence on pathways between gender equality, women's empowerment, and food systems. The paper uses an adaptation of the food systems framework to organize the evidence and identify where evidence is strong, and where gaps remain. Results show strong evidence on women's differing access to resources, shaped and reinforced by contextual social gender norms, and on links between women's empowerment and maternal education and important outcomes, such as nutrition and dietary diversity. However, evidence is limited on issues such as gender considerations in food systems

ABOUT THE AUTHORS

Jemimah Njuki, Director for Africa, International Food Policy Research Institute (IFPRI)

Sarah Eissler, Independent consultant

Hazel Malapit, Senior Research Coordinator, IFPRI, Washington DC.

Ruth Meinzen-Dick, Senior Research Fellow, IFPRI, Washington DC.

Elizabeth Bryan, Senior Scientist, IFPRI, Washington DC

Agnes Quisumbing, Senior Research Fellow, IFPRI, Washington DC

for women in urban areas and in aquaculture value chains, best practices and effective pathways for engaging men in the process of women's empowerment in food systems, and for addressing issues related to migration, crises, and indigenous food systems. While there are gender-informed evaluation studies examining the effectiveness of gender- and nutrition-sensitive agricultural programs, evidence to indicate the long-term sustainability of such impacts remains limited. The paper recommends keys areas for investment: improving women's leadership and decision-making in food systems, promoting equal and positive gender norms, improving access to resources, and building cross-contextual research evidence on gender and food systems.

1. INTRODUCTION

Women are key actors in food systems as producers, wage workers, processors, traders, and consumers. They do this work despite many constraints and limitations including lower access to opportunities, technologies, finance and other productive resources, and weak tenure and resource rights. These constraints and limitations are shaped and reinforced by social and structural inequalities in food systems. Stark gender inequalities are both a cause and outcome of unsustainable food systems and unjust food access, consumption, and production. In the agriculture sector, for example, evidence shows that women have unequal access and, in some cases, unequal rights, to important resources, such as land, water, pasture, seeds, fertilizers, chemical inputs, technology and information, and extension and advisory services, which reduces their potential to be productive in agriculture, become empowered to make strategic decisions and act on those decisions, and realize their rights (Doss 2018; Meinzen-Dick et al. 2019; Mulema and Damtew 2016; Madzorera and Fawzi 2020). In addition, compared with men, women are more vulnerable to chronic food and nutrition insecurity as well as shock-induced food insecurity (Madzorera and Fawzi 2020; Theis et al. 2019).

2. CONCEPTUAL FRAMING

We conceptualize gender as an important lever for progress across all aspects of food systems (Figure 1) and draw upon key terms and definitions of women's empowerment, women's economic empowerment, and gender-transformative approaches (see definitions in annex 1). Food system drivers are anchored in a gendered system with structural gender inequalities and are shaped by shocks and vulnerabilities that affect men and women in different ways. Structural gender inequalities and gendered shocks and vulnerabilities thus influence the ways in which men and women experience these drivers of food systems, which in turn shape the three main components of food systems: value chains, the food environment, and consumer behavior.

This conceptualization of gender in food systems recognizes and highlights the linkages and interconnectedness across these components of food systems—value chains, food environments, and consumer behavior. For example, strengthened access to nutritious foods (food environment) is an important source and pathway to strengthening individual and household resilience (drivers), particularly as adverse effects of climate change will continue to negatively influence access to and consumption of diverse nutrient-rich foods (Fanzo et al. 2018; Theis et al. 2019). And as food systems are both contributors to and impacted by climate change, nature-positive production schemes (production), such as sustainable agricultural intensification strategies, enable food systems to reduce their contribution to and mitigate the impacts of climate change, thus strengthening resilience (drivers) (Campbell et al. 2014).

These three components of the food system interact with gender equality /inequality in a four-dimensional space: individual and systemic, formal and informal. Transforming food systems in equitable ways requires changes in gender equality at the individual and systemic levels and at the formal and informal levels. Consciousness and awareness (individual; informal) are the changes that must occur in women's and men's consciousness, capacities, and behavior. Access to resources and opportunities (individual, formal) are the changes that must occur with regard to one's access to resources, services, and opportunities. Informal cultural norms and deep structure (informal, systemic) are the changes that must occur in the deep structure and implicit norms and social values that undergird the way institutions operate, often in invisible ways. Finally, formal policies, laws, and institutional arrangements (formal, systemic) are the changes that must be made to policies and laws in place to protect against social and gender discrimination and advance equality

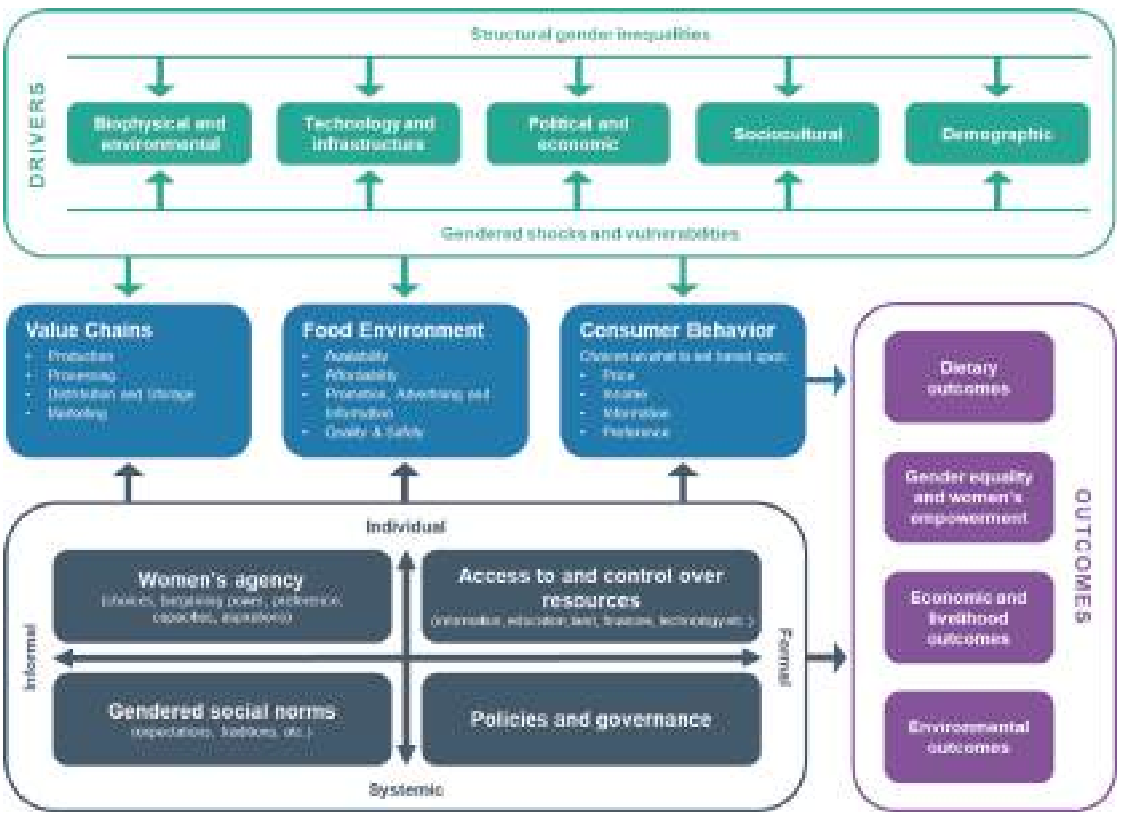
1 See Johnson et al. (2018) for a discussion of the Reach-Benefit-Empowerment framework.

(Gender at Work n.d.). Change must go beyond simply reaching women through interventions and requires facilitating the empowerment process so that women can benefit from food system activities (namely increasing wellbeing, food security, income, and health) and can make and act upon strategic life decisions within food systems.[1] Women's agency, differences in access to and control over resources, gendered social norms, and existing policies and governance influence how men and women can participate in and benefit from food systems, leading to differences in overall outcomes (Figure 1).

3. METHODOLOGY

This paper uses a scoping review (Harris et al. 2021; Liverpool-Tassie et al. 2020) to assess the current evidence on gender issues in food systems. Given the broad range of key topics related to gender in food systems, topically relevant and published systematic reviews were purposively sampled to provide a baseline state of the evidence. After purposively sampling and identifying 16 systematic and scoping reviews to inform the baseline, additional articles were collected. Three databases (Google Scholar, ScienceDirect, and IFPRI's Ebrary) were used to gather and collect additional articles using key word searches aligned with 42 unique terms cross-referenced with the terms "gender" and "women." A total of 198 articles were selected from these databases for review after meeting the following inclusion criteria: the articles must be empirical and peer-reviewed, published in English, and have a geographic focus in low- or middle-income countries (LMICs). The article must also make an explicit reference to gender or women's empowerment and the key thematic term. For articles meeting these initial criteria, additional criteria were used to exclude some from the review, including if the methodology was inadequate to account for biases, or if the article was not relevant to agriculture or food systems. Duplicate articles from across the searches were eliminated from the database. Finally, additional articles were identified for inclusion from the citations in the articles collected above. All collected articles were managed in Zotero reference manager software.[2]

Figure 1 Gendered Food Systems



Source: Adapted from de Brauw et al. (2019).

2 All articles reviewed for this paper are compiled in a separate Excel database, with the following metrics collected for each article: author(s) name, article title, year published, journal or organization of publication, country focus (if specified), region focus, methods used, and main finding(s). Additional information on the search methods and articles selected are included in the full review paper (citation forthcoming).

4. FINDINGS

This section presents the main findings of evidence relevant to the components of the gendered food systems conceptual framework (Figure 1): drivers and cross-cutting levers, shocks and stressors, food and value chains, food environment, consumer behavior, and outcomes.

In general, the evidence reveals that women are important actors and contributors to food systems, but their contributions are typically undervalued, unpaid, or overlooked in food systems research. A 2021 map of food systems and nutrition evidence from 3ie indicates that although women have a major role in food systems, relatively few studies have examined strategies for or the effectiveness of interventions aimed at improving women's decision-making power or have measured outcomes related to empowerment (Moore et al. 2021). Many food system interventions have not collected evidence regarding gender, an oversight that may result in poor outcomes or inefficient use of funds to improve food systems (Moore et al. 2021).

Overall, the literature is largely in agreement as to how to advance gender equality and women's empowerment in food systems but offers little evidence on causal pathways or mechanisms (Moore et al. 2021). The existing evidence, in general, offers locally or contextually specific findings; limited evidence exists that applies across contexts or at geographic scale.[3]

Drivers: Shocks and Stressors

Men and women are differently exposed and vulnerable to shock and stress events. As a result of social norms and differing access to important resources, men and women have different capacities to mitigate risk and respond to these events (Mahajan 2017; Codjoe et al. 2012). The types of capacities needed include absorptive, adaptive, and transformative capacities, which are built by developing and leveraging resources and networks to reduce the risk of adverse impacts and facilitate faster recovery from shock and stress events. Gendered impacts of shocks are nuanced, context-specific, and often unexpected (Quisumbing et al. 2018; Rakib and Matz 2014; Nielsen and Reenberg 2010). Gendered perceptions of climate change and ensuing effects are based on livelihood activities and household and community roles and responsibilities, and often influence how men and women can leverage adaptation strategies to respond (Quisumbing et al. 2018; Aberman et al. 2015; Nielsen and Reenberg 2010).

Many studies indicate that gender-differentiated access to or ownership of important resources— such as women having fewer assets and lacking access to information services or credit—is linked to different capacities to mitigate, adapt to, and recover from shock and stress events (Bryan et al. 2013; de Pinto et al. 2020; Fisher and Carr 2015). However, women's participation in collaborative farming schemes or group networks facilitates broader access to resources and additional social networks and types of social capital, which strengthen women's capacity to respond to these events (Vibert 2016). For example, participation in community groups and access to credit options have been positively associated with uptake of climate-smart agriculture practices and technologies in Mali (Ouédraogo et al. 2019).

Women have fewer adaptation options than men, as social norms restrict women's mobility, freedom of movement, and access to transportation, as do time burdens associated with domestic and care responsibilities (Jost et al. 2016; Naab and Koranteng 2012; de Pinto et al. 2020). However, de Pinto et al. (2020) note evidence that certain components of women's empowerment led to increased crop diversification among small-scale agricultural producers in Bangladesh, suggesting that women do play an important and positive role in climate change adaptation. Access to context-specific and relevant climate information and appropriate technologies is a key determinant of adopting climate change adaptation practices, and women and men have different needs for and access to such information (see section below on Gendered Access to Services and Technology) (Bryan et al. 2013; Tambo and Abdoulaye 2012; Twyman et al. 2014; Mudege et al. 2017).

Food System Components

Agrifood Value Chains

Women are actively engaged across various roles in agricultural value chains, although women's positions are typically undervalued and overlooked in food systems research (Doss 2013). In Ethiopia, Abate (2017) found that women were predominately responsible for storage preparation, postharvest processing, milk

3 The findings presented in this paper are high-level. Nuanced and further explanation of findings can be found in the full review paper (citation forthcoming).

processing, barn cleaning, care for newborn livestock, cooking, grinding, fetching, and collecting fuelwood, and worked with men to weed, harvest, thresh, and protect crops from wildlife. Qualitative evidence from Benin suggests that women are predominately engaged in agricultural processing activities and, if they have access to land, they are also engaged in production activities (Eissler et al. 2021a). Studies from Benin and Tanzania also found that, regardless of the producer, men manage higher-value sales and marketing, while women only manage marketing and negotiation of small-value sales (Eissler et al. 2021a; Mwaseba and Kaarhus 2015). Gupta et al. (2017) provided evidence that improving women's market access is strongly correlated with increased levels of women's empowerment in India.

Agriculture both contributes to and is affected by anthropogenic climate change. As population pressures continue to increase and place demands on food production, agricultural livelihoods across agrifood value chains must adapt approaches that will sustainably meet rising demand, reduce risk associated with adverse climatic events, and mitigate contributions to climate change. Such approaches include sustainable intensification (Tilman et al. 2011; Rockström et al. 2017), conservation agriculture (Montt and Luu 2020), and climate-smart and climate-resilient agriculture (Gutierrez-Montes et al. 2020; Duffy et al. 2020), among others. A growing body of evidence indicates that women producers are less able to adopt such sustainable and resilient production practices or methods given their limited access to necessary resources, including land, time, labor, information, and technologies (Theriault et al. 2017; Ndiritu et al. 2014; Grabowski et al. 2020; Farnworth et al. 2016; Meinzen-Dick et al. 2019; Doss et al. 2015; Perez et al. 2015; Pradhan et al. 2019; Parks et al. 2014; Ayantunde et al. 2020; Khoza et al. 2020; Gathala et al. 2021; Mont and Luu 2018; Beuchelt and Badstue 2013; Halbrendt et al. 2014).

Food Environment

Several themes emerge from the evidence linking gender equality and women's empowerment with improving availability and access to safe and nutritious food. First, the affordability of nutritious food is an important issue for accessing nutrient-rich foods to advance gender equality and women's empowerment. Available evidence indicates that women are less likely than men to be able to afford a nutritious diet, as women often occupy lower-paying wage positions than men, earn and control smaller incomes than men, have less autonomy over household financial decisions, or have no income at all. For example, Raghunathan et al. (2021) estimated that while nutritious diets have become substantially more affordable for women and men wage workers in rural India, unskilled wage workers still cannot afford a nutritious diet; unskilled workers account for approximately 80 to 90 percent of female and 50 to 60 percent of male daily wage workers and affect 63 to 76 percent of poor rural children.

Another important theme is ensuring equitable access to markets where nutritious foods can be purchased. Nutrient-dense foods, such as fruit, milk, and vegetables, are difficult to transport and store, and therefore must be purchased locally, particularly in remote and rural areas (Hoddinott et al. 2015; Mulmi et al. 2016). Several articles linked women's mobility and freedom of movement to market access, and thus to positive nutrition and food security outcomes. For example, Aryal et al. (2018) found that physical distance to markets impacted household food security outcomes for female-headed households more than for male-headed households in Bhutan. Shroff et al. (2011) found women's low autonomy in mobility was positively associated with wasting in children in India. The evidence seems to associate women's limited mobility with stricter social gender norms and religion.

Consumer Behavior

Agriculture can influence diets and dietary choices through the consumption of household-produced crops or increased purchasing power derived from the sale of agricultural products. Moore et al. (2020) found that in research since 2000, women's roles in food systems are mostly examined in terms of their role as consumers, such as household cooks, or as mothers who are breastfeeding or whose health affect that of their children. Other studies link gender norms, roles, and responsibilities to women as food preparers and managers of household diet quality (Eissler et al. 2020a; Sraboni and Quisumbing 2018). Komatsu et al. (2018) found a positive association between the amount of time women spent on food preparation and household dietary diversity, and Chaturvedi et al. (2016) found a positive association between the time mothers spent with their children and nutrition status.

There is evidence showing positive effects of nutrition counseling, nutrition education, and maternal education for nutrition, dietary diversity, and health outcomes for women and children (Choudhury et al. 2019; Atker et al. 2012; Kimambo et al. 2018; Reinbott and Jordan 2016; Reinbott et al. 2016; Rakotomanana et al. 2020; Ragasa et al. 2019). Interventions for sustainable and nutritious diets are found to be more effective when they include components on nutrition and health behavior change communication, women's empowerment, water, sanitation, and hygiene

(WASH), and micronutrient-fortified products (Ruel et al. 2019). Gelli et al. (2017) found preliminary evidence that WASH components of a nutrition-sensitive agriculture intervention can mitigate the potential harm, such as the health risks, of introducing and enhancing small livestock production in Burkina Faso. However, more evidence is needed to understand best practices for reducing potential harm of increased livestock production and management in nutrition-sensitive agricultural programs (Ruel et al. 2019).

Food System Outcomes

Recent research has examined the link between maternal mental health and psychosocial indicators and nutrition outcomes. There is mixed evidence regarding the link between maternal depression and mental health symptoms and child or household nutrition. Wemakor and Iddrisu (2018) found no association between maternal depression and child stunting in northern Ghana, whereas Wemakor and Mensah (2016) and Anato et al. (2020) found positive associations between women experiencing depressive symptoms and child undernutrition in Ghana and Ethiopia. Wemakor and Mensah (2016) observed that women experiencing the highest levels of depression were also those with lowest incomes or from the lowest-income households. Cetrone et al. (2021) found that food security improvements resulting from participation in a nutrition-sensitive agriculture program mediated women's depression symptoms in Tanzania. Such evidence, which is both mixed and limited, suggests that further studies are needed to understand the psychosocial impacts of women's empowerment and mental health on household nutrition and health outcomes.

Evidence links access to resources and empowerment to nutritional outcomes and children's educational outcomes. For example, evidence indicates that women's livestock ownership or production diversity, combined with market access and women's empowerment, are important drivers of diverse household consumption and nutritional status (Sibhatu et al. 2015; Mulmi et al. 2016; Hodinott et al. 2015). Additionally, Malapit et al. (2018) found in Bangladesh that while gaps in parental empowerment had only weak associations with children's nutrition status, mother's empowerment is positively associated with girls' education and keeping older children in school in general.

A growing body of research has examined the pathways through which women's empowerment is linked with household nutrition outcomes and access to nutritious foods (Alaofè et al. 2017; Reinbott and Jordan 2016; Bellows et al. 2020; Malapit and Quisumbing 2015; Heckert et al. 2019; Lentz et al. 2021). These pathways are contextual and vary across countries and regions (Na et al. 2015; Ruel et al. 2019; Quisumbing et al. 2020). Ruel et al. (2019) observe that while the current evidence broadly associates women's empowerment and nutrition outcomes, this evidence is generally context-specific, given that women's empowerment and gender roles and norms are closely linked. As more evidence is generated from cross-context evaluations, future research can create typologies to better explain how gender roles more broadly interact with nutrition-sensitive agricultural interventions (Ruel et al. 2019).

Specific to equitable livelihood outcomes, evidence indicates that women face disproportionate barriers in accessing finance and credit options compared with men (Adegbite et al. 2020; Ghosh and Vinod 2017; Dawood et al. 2019; Kabir et al. 2019). For example, Kabir et al. (2019) found that in Bangladesh, a lack of access to credit is the most significant barrier women producers faced, followed by lack of need-based training, high interest rates, insufficient land access, and a lack of quality of seeds. Women's ability to earn incomes and participate in income-generating activities are strongly mediated by restrictive gender norms, lack of access to resources, and time burdens arising from normative roles and responsibilities. In a study of urban women vegetable traders in Viet Nam, Kawarazuka et al. (2017) found that women were able to work in less socially respected spaces, such as street trading, but still needed to negotiate their access to informal employment spaces with their husbands.

Supporting women's entrepreneurship is suggested as an important pathway to advancing gender equality and women's empowerment in food systems. Malapit et al. (2019) suggests that this is not necessarily the case if these businesses are small and home-based; such businesses typically make little profit and tend to add to women's existing time burdens. And in a systematic literature review, Wolf and Frese (2018) emphasized the need to recognize that spousal support is a key factor for women's entrepreneurship or engagement in income-generating activities.

5. CROSS-CUTTING GENDER AND FOOD SYSTEM ISSUES

Gendered Social Norms and Expectations

Social and cultural norms shape and reinforce the ways in which women and men can participate in, access, and benefit from opportunities and resources (Kristjianson et al. 2017; Meinzen-Dick et al. 2019; Rao et al. 2017; Moosa and Tuana 2014). This has important consequences across all aspects of advancing women's empowerment and gender equality in food systems. For example, norms can hinder women's ability to access or adopt new agricultural practices (Kiptot and Franzel 2012; Njuki et al. 2014). Importantly, gender norms vary within contexts, such as by religious identity or social class. Kruijssen et al. (2016) noted that different normative expectations of women in Hindu and Muslim communities influenced the ways in which these women were constrained or enabled in participating in aquaculture value chains in Bangladesh.

In general, women often experience restrictive social norms that hinder their empowerment and full participation in household or community activities and value chains (Huyer and Partey 2019; Kruijssen et al. 2018). In a review of evidence on gender issues in global aquaculture value chains, Kruijssen et al. (2018) found that contextual gender norms shape the ways in which women and men participate in aquaculture value chains around the world, often limiting women's ability to participate in and benefit from aquaculture value chains equally.

Social gender norms are contextually and culturally specific and are strongly linked to women's empowerment (Eissler et al. 2020a, 2020b, 2021a; Meinzen-Dick et al. 2019; Bryan and Garner 2020). Emic understandings of an empowered woman and an empowered man vary, but importantly inform the understanding of cultural nuances and expectations of roles and responsibilities of women (Meinzen-Dick et al. 2019; Bryan and Garner 2020). Men are generally considered household financial providers and decision-makers, whereas women are responsible for domestic chores, childcare, food preparation, and other unpaid care tasks. In rural agricultural settings, women may also provide household labor on their husbands' agricultural plots in addition to their domestic work yet are not remunerated for this labor (Picchioni et al. 2020; Nahusenay 2017; Ghosh and Chopra 2019). Recent evidence also suggests that patterns of male dominance in the household are linked to individuals' gender norms but are not necessarily correlated with intergenerational transfers of male dominance in intrahousehold decision-making (Leight 2021).

Gendered Access to and Control over Resources, Services, and Technology

A large body of literature has examined differences in men's and women's access to, ownership of, and control over resources in the food system (Johnson et al. 2016; Uduji et al. 2019; Perez et al. 2015; Gebre et al. 2019; Fisher and Carr 2015; Lambrecht and Mahrt 2019). Evidence indicates that perceived or effective ownership of resources may be more important than actual ownership for women's empowerment and nutrition outcomes (Eissler et al. 2020b). Studies have found positive associations between women's land ownership and their participation in community groups or co-operative networks, suggesting that access to important resources, such as land, facilitates access to other resources, such as increased bargaining power and pooled assets. Further evidence indicates that when women's previously less-lucrative or lower-valued activities begin to rise in value or earn higher incomes, control over the activity or resource may be transferred from women to men (Mwaseba and Kaarhus 2015).

Existing literature shows that women face social, cultural, and institutional barriers to accessing and adopting agricultural technologies, information, and services (Peterman et al. 2014; Peterman et al. 2011; Perez et al. 2015; Mudege et al. 2015, 2017; Ragasa et al. 2013; de Pinto et al. 2020; Raghunathan et al. 2019; Duffy et al. 2020). Men and women have different needs for and access to such information and technologies; gender analyses are therefore needed to tailor communication strategies to ensure that information and dissemination are adequately targeted to men and women (Tall et al. 2014; Peterman et al. 2014; Diouf et al. 2019; Ragasa et al. 2013; Jost et al. 2016; Mudege et al. 2017; Duffy et al. 2020). Women have access to disproportionately less information than men overall but they have access to more information regarding certain topics relevant to their gender-normative roles and responsibilities, such as postharvest handling and small livestock production (Twyman et al. 2014).

Gender-sensitive program designs that aim to increase access to technologies have positive impacts on women's nutrition and health outcomes (Kassie et al. 2020; Alaofè et al. 2016, 2019). An evaluation of a gender-sensitive irrigation intervention in northern Benin found that women in the program had higher dietary diversity, increased intake of vegetables, reduced rates of anemia, higher body mass indexes (BMI), and improved household nutritional status through direct consumption as a result of women's increased crop diversification and women's increased income allowing them to make economic decisions (Alaofè et al. 2016, 2019).

Interventions to benefit or empower women may overlook the time trade-offs required for women's participation or for intended outcomes (Picchioni et al. 2020; Komatsu et al. 2018; van den Bold et al. 2020). Importantly, measuring time use itself does not address women's agency over their time use or the intra-household decision-making surround-ing how and on what activities women may spend their time (Eissler et al. 2021b). There is little research to show how women may control their own time use or how interventions can support women in managing their own time to advance their strategic choices in food systems.

Women's Agency: Decision-Making and Leadership

Household Level
Evidence suggests positive nutrition, livelihood, well-being, and resilience outcomes when women are more involved and have greater influence in household decision-making. Several studies find that when women own or have joint title to land, they are significantly more involved or have greater influence in household decision-making, particularly regarding agricultural or productive decisions (Wiig 2013; Mishra and Sam 2016). And while Fisher and Carr (2015) found that women farmers in Ghana and Malawi were less likely to adopt drought-tolerant maize varieties due to differences in resource access, women strongly influenced the adoption of drought-tolerant maize varieties on plots controlled by their husbands.

Community Level
Diiro et al. (2018) found evidence that increases in women's empowerment, including women's participation in community leadership, is associated with higher agricultural productivity; and women from more food-secure households are more likely to participate in community leadership roles. Niewoehner-Green et al. (2019) found that for women in rural Honduras, social norms and structural biases hindered their participation in leadership positions in agricultural groups and limited their influence and voice in community decisions. There is some evidence to suggest that men and women value and participate in different types of community groups. For example, women place a higher value on savings and credit groups than men and may have greater access to hyper-local institutions, whereas men have greater access to institutions and services from outside of their immediate community (Cramer et al. 2016; Perez et al. 2015). Other evidence suggests that women may participate in fewer groups than men (Mwongera et al. 2014).

Food Systems Level
Increasing women's voices and integrating their preferences into agricultural solutions, including technology design and implementation, is an under-researched pathway to empowerment and gender equality in food systems. For example, there is evidence that women may have different preferences than men with regard to crop varietals (Gilligan et al. 2020; Teeken et al. 2018), but there is limited evidence that breeders' consider these preferences in varietal design and profiles (Tufan et al. 2018; Marimo et al. 2020).

Institutional Barriers, Policy, and Governance
The prevalence of gender-based violence (GBV) is a systemic barrier for women's empowerment in food systems. There is extensive research in health literature on GBV; however, research on violence against women in the context of food systems is limited. Some studies find evidence that women's asset ownership deters GBV, suggesting that when women own assets, their status may increase, making it easier for them to leave harmful relationships (Grabe 2010; Grabe et al. 2015). Buller et al. (2018) and Lees et al. (2020) found that cash transfer programs decrease the incidence of GBV. The new project-level Women's Empowerment in Agriculture Index for Market Inclusion (pro-WEAI+MI) includes indicators on sexual harassment and violence against women in composite measurements of empower-ment for women in agricultural value chains (Ragasa et al. 2021; Eissler et al. 2021a), providing a tool to measure the incidence of GBV and its impact on women's empowerment in food systems.

Institutions and policies that support gender equality and women's empowerment in food systems are generally lacking in low-income countries (Meinzen-Dick et al. 2013). Bryan et al. (2017) observed that a lack of policies and institutional capacity hinders research and gender integration into climate change adaptation programs across a range of contexts, specifically noting a lack of staff capacity on gender, lack of funding to support gender integration, and sociocultural constraints as key barriers to gender integration. Some evidence suggests a tension between formal legislation and practiced law. Pradhan et al. (2019) found that in practice, women's joint and personal property rights differ from legal definitions. Eissler et al. (2021a) observed that while Benin has formal gender equality and antidiscrimination laws, these are poorly enforced and do not align with social norms toward GBV or harassment. For example, women working in agricultural value chains often may not report incidents of sexual harassment in the workplace for fear of upsetting their husbands, suggesting that women may feel a sense of responsibility for inviting the harassment.

6. CONCLUSIONS

This scoping review aimed to elucidate evidence and identify evidence gaps for advancing gender equality and women's empowerment in food systems. We see evidence that women have differing access to resources compared with men, such as essential services, knowledge and information, technology dissemination, land, credit options, time, and markets. This differing level of access is shaped and reinforced by contextual social gender norms. Existing evidence shows that context-specific pathways link women's empowerment to important outcomes, such as household nutrition and dietary diversity, noting that these pathways may vary between and within contexts. Cross-contextual evidence exists of positive associations between maternal education (and specifically, access to nutrition education) and positive outcomes for child and household nutrition and diet quality.

While this review was not systematic, it appears that only limited studies address important areas of inquiry regarding gender equality and women's empowerment in food systems. Specifically, only a few studies included in this review examined gender considerations in food systems for women in urban areas or aquaculture value chains. There have been few studies to understand best practices and effective pathways for engaging men in the process of women's empowerment in food systems, or addressing issues of migration, crises, or indigenous food systems. Additionally, while there are gender-informed evalua-tion studies examining the effectiveness of gender- and nutrition-sensitive agricultural programs, there is limited evidence to indicate the long-term sustainability of such impacts.

In conclusion, this review suggests there is substantial agreement about pathways to improve women's empowerment and gender equality in food systems, but the actual evidence to support these pathways, specifically cross-contextual evidence, is limited. Existing evidence is extremely localized and context-specific, limiting its application beyond the focus area of the study. And finally, relatively few studies included a gender-informed design and conceptual framework to best understand mechanisms to promote equality and empowerment. Moving forward, further research is required to produce stronger evidence on cross-contextual pathways to improve gender equality and women's empowerment in food systems.

7. RECOMMENDATIONS FOR INVESTMENT

Invest in maternal education, particularly nutrition-focused education and counseling.

Cross-contextual evidence indicates that maternal education and experiences with nutrition counseling are positively associated with improved diet quality and diversity, leading to better nutrition outcomes at the household level. For example, Chudhury et al. (2019) found a positive association of maternal education and maternal health, household dietary diversity, and nutrition and health outcomes for household members in 42 countries, suggesting that dietary diversity may be driven by preferences and knowledge. In Tanzania, Kimambo et al. (2018) found positive associations between women's nutrition knowledge and consumption of African vegetables. Rakotomanana et al. (2020) found that in Madagascar, children of mothers with knowledge and positive attitudes about complementary nutrient-rich foods had more nutrient-diverse diets; and those with mothers who had lower incomes and greater time burdens had less nutrient-diverse diets. Studies also found benefits from involving grandmothers in nutrition counseling, education, and dialogues in Sierra Leone (Aidam et al. 2020; MacDonald et al. 2019) and Nepal (Karmacharya et al. 2017). Investments should focus on increasing women's educational attainment coupled with nutrition-focused counseling.

Invest in programs/interventions that aim to improve women's influence and role in decision-making and leadership at all levels of the food system (household, community, and systems).

Women's influence and role in decision-making is associated positively with nutrition, women's empowerment, and livelihood outcomes at all levels of food systems. At the household level, in northern Ghana, for example, women are less likely to have decision-making autonomy over productive decisions, purchasing, selling or transferring assets, and speaking in public (Ragsdale et al. 2018). In Bangladesh, de Pinto et al. (2020) found that households have higher levels of crop diversification when women have more influence in productive household decision-making, suggesting that an increase in women's bargaining power can lead to more resilient agricultural livelihoods. At the community level, evidence indicates that women's participation in community groups also enhances resilience, increases access to important resources such as land or labor, builds and facilitates social networks, and increases their influence and participation in community-level decision-making (Kumar et al. 2019; Aberman et al. 2020). For example, Kabeer (2017) found that women in Bangladesh who expand their active social networks through community groups have higher levels of empower-ment. Raghunathan et al. (2019) found that Indian women's participation in self-help groups was positively associated with increased levels of information and participation in some agricultural decisions but did not affect agricultural production or outcomes, possibly because of women's limited time, financial constraints, or restrictive social norms. At the systems level, there is limited evidence to suggest that technology development (including crop breeding, for example) incorporates women's different preferences and needs into design (Tufan et al. 2018; Marimo et al. 2020). Investments should be made in interventions that address and facilitate improvements for women's influence and participation in decision-making at all levels.

Invest in interventions that promote positive and equal gender norms at the household, community, and systems level.

Gender norms and associated expectations vary by context; however, restrictive gender norms shape and, in many ways, hinder women's empowerment across contexts and limit their ability to participate in and act upon strategic decisions or activities to advance their own empowerment across all components of food systems. For example, a study in Egypt found that a woman's normative role as an unpaid household caregiver limited her ability to sell fish compared with her husband, who did not face time burdens associated with caregiving and who maintained decision-making control over his and his wife's activities (Kantor and Kruijssen 2014). In Papua New Guinea, Kosec et al. (2021) found that men are more likely to support women challenging normative gender roles in terms of their economic participation during periods of household economic stress because this can raise household income, not because they support transforming women's role in society more generally. Contextual gender norms may also shape women's food allocation preferences, which hold important implications for nutrition. In Ethiopia, for example, women may favor sons over daughters for more nutrient-dense foods (Coates et al. 2018). Sraboni and Quisumbing (2018) found that women's preferences in allocating nutritious foods were influenced heavily by social norms in Bangladesh, where women favored sons over daughters because of male advantage in labor markets and property rights. Investments should be made to promote positive and equal gender norms for and with men and women across contexts and scales from the household to system levels.

Invest in interventions and efforts that improve women's access to important and necessary resources.

The evidence overwhelmingly indicates that across contexts women have less access to important resources than men. These resources include, but are not limited to, land, agricultural inputs, financing options, financial services, technology, technical services, and time. Nuanced variations exist across and within contexts. For example, in sub-Saharan Africa, studies indicate that women may rely on informal sources of information, such as personal connections, whereas men rely on formal sources of information, such as extension or the private sector; however, in Colombia, men may have more access to information overall compared to women, but both rely on the same sources of information (Twyman et al. 2014, 2016; Mudege et al. 2017). With regard to time, Komatsu et al. (2018) found that women's time allocation and household nutrition outcomes varied by local context, such that women's time in domestic work was positively associated with diverse diets in Bangladesh, Cambodia, Ghana, Mozam-bique, and Nepal, but in Mozambique, the relation between women's time in agricultural work and children's diet quality varied with women's asset poverty. Picchioni et al. (2020) found that in India and Nepal, women and men participate equally in productive work that requires high levels of energy, but women shoulder most of the reproductive work at the expense of leisure opportunities. Van den Bold et al. (2020) found that a nutrition-sensitive agricultural intervention in Burkina Faso significantly increased the time women spent on agriculture and led to improved maternal and child nutrition outcomes, and that women's increased time spent on agriculture did not have deleterious effects on their own or their children's nutrition. Investments should be made to target improving women's access to and control and ownership over such resources to ensure they are able to effectively benefit from these resources.

Target research to yield more cross-contextual evidence for advancing gender equality and women's empowerment in food systems.

Finally, the overall outcome of this review revealed that the current evidence on advancing women's empowerment and gender equality in food systems is locally specific and linked to contextual gender norms. Developing cross-contextual typologies can support development of evidence that has broader application. More targeted research is required to identify patterns of successful and effective interventions and pathways to advance women's empowerment and gender equality in food systems with contextual norms. The outcome of such research would be clear typologies that link successful interventions and recommenda-tions by gender norms.

REFERENCES

1. Abate, N. 2018. "An Investigation of Gender Division of Labour: The Case of Delanta District, South Wollo Zone, Ethiopia." Journal of Agricultural Extension and Rural Development 9(9): 207–214.
2. Aberman, N., S. Ali, J. Behrman, E. Bryan, P. Davis, A. Donnelly, V. Gathaara, D. Kone, T. Nganga, J. Ngugi, B. Okoba, and C. Roncoli. 2015. "Climate Change Adaptation Assets and Group-Based Approaches: Gendered Perceptions from Bangladesh, Ethiopia, Mali, and Kenya." IFPRI Discussion Paper 01412, International Food Policy Research Institute, Washington, DC.
3. Aberman, N., R. Birner, E. Auma Okiri Odoyo, M. Oyunga, B. Okoba, and G. Okello. 2020. "Gender-Inclusive Governance of 'Self-Help' Groups in Rural Kenya." IFPRI Discussion Paper 01986, International Food Policy Research Institute, Washington, DC.
4. Adegbite, O., and C. Machethe. 2020. "Bridging the Financial Inclusion Gender Gap in Smallholder Agriculture in Nigeria: An Untapped Potential for Sustainable Development." World Development 127(March): 104755.
5. Aidam, B., C. MacDonald, R. Wee, J. Simba, J. Aubel, K. Reinsma, and A. Girard. 2020. "An Innovative Grandmother-Inclusive Approach for Addressing Suboptimal Infant and Young Child Feeding Practices in Sierra Leone." Current Developments in Nutrition 4(12): nzaa174.
6. Akter, R., N. Yagi, H. Sugino, S.H. Thilsted, S. Ghosh, S. Gurung, K. Heneveld, R. Shrestha, and P. Webb. 2020. "Household Engagement in Both Aquaculture and Horticulture Is Associated with Higher Diet Quality than Either Alone." Nutrients 12(9): 2705.
7. Alaofè, H., J. Burney, R. Naylor, and D. Taren. 2016. "Solar-Powered Drip Irrigation Impacts on Crops Production Diversity and Dietary Diversity in Northern Benin." Food and Nutrition Bulletin 37(2): 164–75.
8. Alaofè, H., J. Burney, R. Naylor, and D. Taren. 2016. "The Impact of a Solar Market Garden Programme on Dietary Diversity, Women's Nutritional Status and Micronutrient Levels in Kalalé District of Northern Benin." 2019. Public Health Nutrition 22(14): 2670–2681.
9. Anato, A., K. Baye, Z. Tafese, and B.J. Stoecker. 2020. "Maternal Depression Is Associated with Child Undernutrition: A Cross-Sectional Study in Ethiopia." Maternal & Child Nutrition 16(3): e12934.
10. Aryal, J.P., D.B. Rahut, K.A. Mottaleb, and A. Ali. 2019. "Gender and Household Energy Choice Using Exogenous Switching Treatment Regression: Evidence from Bhutan." Environmental Development 30 (June): 61–75.
11. Ayantunde, A.A., B.O. Oluwatosin, V. Yameogo, and M. van Wijk. 2020. "Perceived Benefits, Constraints and Determinants of Sustainable Intensification of Mixed Crop and Livestock Systems in the Sahelian Zone of Burkina Faso." International Journal of Agricultural Sustainability 18(1): 84–98.
12. Bellows, A.L., C.R. Canavan, M.M. Blakstad, D. Mosha, R.A. Noor, P. Webb, J. Kinabo, H. Masanja, and W.W. Fawzi. "The Relationship Between Dietary Diversity Among Women of Reproductive Age and Agricultural Diversity in Rural Tanzania." Food and Nutrition Bulletin 41(1): 50–60.
13. Beuchelt, T.D., and L. Badstue. 2013. "Gender, Nutrition- and Climate-Smart Food Production: Opportunities and Trade-Offs." Food Security 5(5): 709–21.
14. Van den Bold, M., L. Bliznashka, G. Ramani, D. Olney, A. Quisumbing, A. Pedehombga, and M. Ouedraogo. 2021. "Nutrition-Sensitive Agriculture Programme Impacts on Time Use and Associations with Nutrition Outcomes." Maternal & Child Nutrition 17(2): e13104.
15. Bryan, E., C. Ringler, B. Okoba, C. Roncoli, S. Silvestri, and M. Herrero. 2013. "Adapting Agriculture to Climate Change in Kenya: Household Strategies and Determinants." Journal of Environmental Management 114(January): 26–35.
16. Bryan, E., and E. Garner. 2020. "What Does Empowerment Mean to Women in Northern Ghana? Insights from Research around a Small-Scale Irrigation Intervention." IFPRI Discussion Paper 01909, International Food Policy Research Institute, Washington, DC.
17. Bryan, E., Q. Bernier, M. Espinal, and C. Ringler. 2018. "Making Climate Change Adaptation Programmes in Sub-Saharan Africa More Gender Responsive: Insights from Implementing Organizations on the Barriers and Opportunities." Climate and Development 10(5): 417–31.
18. Buller, A.M., A. Peterman, M. Ranganathan, A. Bleile, M. Hidrobo, and L. Heise. 2018. "A Mixed-Method Review of Cash Transfers and Intimate Partner Violence in Low- and Middle-Income Countries." The World Bank Research Observer 33(2): 218–58.
19. Campbell, B., P. Thornton, R. Zougmoré, P. van Asten, and L. Lipper. 2014. "Sustainable Intensification: What Is Its Role in Climate Smart Agriculture?" Current Opinion in Environmental Sustainability 8(October): 39–43.
20. Cetrone, H., M. Santoso, L. Petito, R. Bezner-Kerr, L. Blacker, N. Kassim, E. Mtinda, H. Martin, and S. Young. 2020. "A Participatory Agroecological

Intervention Reduces Women's Risk of Probable Depression through Improvements in Food Security in Singida, Tanzania." Current Developments in Nutrition 4(Supplement 2): 819–819.
21. Chaturvedi, S., S. Ramji, N.K. Arora, S. Rewal, R. Dasgupta, and V. Deshmukh. 2016. "Time-Constrained Mother and Expanding Market: Emerging Model of under-Nutrition in India." BMC Public Health 16(July): 632.
22. Choudhury, S., B. Shankar, L. Aleksandrowicz, M. Tak, R. Green, F. Harris, P. Scheelbeek, and A. Dangour. 2020. "What Underlies Inadequate and Unequal Fruit and Vegetable Consumption in India? An Exploratory Analysis." Global Food Security 24 (March): 100332.
23. Coates, J., B.N. Patenaude, B.L. Rogers, A.C. Roba, Y.K. Woldetensay, A.F. Tilahun, and K.L. Spielman. 2018. "Intra-Household Nutrient Inequity in Rural Ethiopia." Food Policy 81(December): 82–94.
24. Codjoe, S., L. Atidoh, and V. Burkett. 2012. "Gender and Occupational Perspectives on Adaptation to Climate Extremes in the Afram Plains of Ghana." Climatic Change 110(1): 431–454.
25. Cramer, L., W. Förch, I. Mutie, and P.K. Thornton. 2016. "Connecting Women, Connecting Men: How Communities and Organizations Interact to Strengthen Adaptive Capacity and Food Security in the Face of Climate Change." Gender, Technology and Development 20(2): 169–99.
26. Dawood, T.C., H. Pratama, R. Masbar, and R. Effendi. 2019. "Does Financial Inclusion Alleviate Household Poverty? Empirical Evidence from Indonesia." Economics & Sociology 12(2): 235–52.
27. De Brauw, A., M. van den Berg, I. Brouwer, H. Snoek, R. Vignola, M. Melesse, G. Lochetti, C. van Wagenberg, M. Lundy, E. d'Hotel, and R. Ruben. 2019. "Food System Innovations for Healthier Diets in Low and Middle-Income Countries." IFPRI Discussion Paper 01816, International Food Policy Research Institute, Washington, DC.
28. De Pinto, A., G. Seymour, E. Bryan, and P. Bhandari. 2020. "Women's Empowerment and Farmland Allocations in Bangladesh: Evidence of a Possible Pathway to Crop Diversification." Climatic Change 163(2): 1025–43.
29. Diiro, G.M., G. Seymour, M. Kassie, G. Muricho, and B.W. Muriithi. 2018. "Women's Empowerment in Agriculture and Agricultural Productivity: Evidence from Rural Maize Farmer Households in Western Kenya." PLOS ONE 13(5): e0197995.
30. Diouf, N.S., I. Ouedraogo, R.B. Zougmoré, M. Ouedraogo, S.T. Partey, and T. Gumucio. 2019. "Factors Influencing Gendered Access to Climate Information Services for Farming in Senegal." Gender, Technology and Development 23(2): 93–110.
31. Doss, C. 2018. "Women and Agricultural Productivity: Reframing the Issues." Development Policy Review 36(1): 35–50.
32. Doss, C. 2013. "Intrahousehold Bargaining and Resource Allocation in Developing Countries1." The World Bank Research Observer 28(1): 52–78.
33. Doss, C., C. Kovarik, A. Peterman, A. Quisumbing, and M. van den Bold. 2015. "Gender Inequalities in Ownership and Control of Land in Africa: Myth and Reality." Agricultural Economics 46(3) 403–434.
34. Doss, C.R., C.D. Deere, A.D. Oduro, H. Swaminathan, Z. Catanzarite, and J.Y. Suchitra. 2019. "Gendered Paths to Asset Accumulation? Markets, Savings, and Credit in Developing Countries." Feminist Economics 25(2): 36–66.
35. Duffy, C., G. Toth, J. Cullinan, U. Murray, and C. Spillane. 2020. "Climate Smart Agriculture Extension: Gender Disparities in Agroforestry Knowledge Acquisition." Climate and Development 13(January): 1–13.
36. Eissler, S., A. Diatta, J. Heckert, and C. Nordhen. 2021a. "A Qualitative Assessment of a Gender-Sensitive Agricultural Training Program in Benin: Findings on Program Experience and Women's Empowerment across Key Agricultural Value Chains." IFPRI Discussion Paper 02005, International Food Policy Research Institute, Washington, DC.
37. Eissler, S., J. Heckert, E. Myers, G. Seymour, S. Sinharoy, and K.M. Yount. 2021b. "Exploring Gendered Experiences of Time-Use Agency in Benin, Malawi, and Nigeria as a New Concept to Measure Women's Empowerment." IFPRI Discussion Paper 02003, International Food Policy Research Institute, Washington, DC.
38. Eissler, S., A. Sanou, J. Heckert, E.C. Myers, S. Nignan, E. Thio, L.A. Pitropia, R. Ganaba, A. Pedehombga, and A. Gelli. 2020a. "Gender Dynamics, Women's Empowerment, and Diets: Qualitative Findings from an Impact Evaluation of a Nutrition-Sensitive Poultry Value Chain Intervention in Burkina Faso." IFPRI Discussion Paper 01913, International Food Policy Research Institute, Washington, DC.
39. Eissler, S., A. Sanou, J. Heckert, E.C. Myers, S. Nignan, E. Thio, L.A. Pitropia, R. Ganaba, A. Pedehombga, and A. Gelli. 2020b. "Gendered Participation in Poultry Value Chains: Qualitative Findings from an Impact Evaluation of a Nutrition-Sensitive Poultry Value Chain Intervention in Burkina Faso." IFPRI Discussion Paper 01928, International Food Policy Research Institute, Washington, DC.
40. Fanzo, J., C. Davis, R. McLaren, and J. Choufani. 2018. "The Effect of Climate Change across Food Systems: Implications for Nutrition Outcomes." Global Food Security 18(September): 12–19.

41. Farnworth, C.R., F. Baudron, J.A. Andersson, M. Misiko, L. Badstue, and C.M. Stirling. 2016. "Gender and Conservation Agriculture in East and Southern Africa: Towards a Research Agenda." International Journal of Agricultural Sustainability 14(2): 142–65.
42. Fisher, M., and E. Carr. 2015. "The Influence of Gendered Roles and Responsibilities on the Adoption of Technologies That Mitigate Drought Risk: The Case of Drought-Tolerant Maize Seed in Eastern Uganda." Global Environmental Change 35(November): 82–92.
43. Gathala, M.K., A.M. Laing, T.P. Tiwari, J. Timsina, F. Rola-Rubzen, S. Islam, S. Maharjan, et al. 2021. "Improving Smallholder Farmers' Gross Margins and Labor-Use Efficiency across a Range of Cropping Systems in the Eastern Gangetic Plains." World Development 138 (February): 105266.
44. Gebre, G.G., H. Isoda, D.B. Rahut, Y. Amekawa, and H. Nomura. 2019. "Gender Differences in Agricultural Productivity: Evidence from Maize Farm Households in Southern Ethiopia." GeoJournal 86(November): 843–864.
45. Gelli, A., E. Becquey, R. Ganaba, D. Headey, M. Hidrobo, L. Huybregts, H. Verhoef, R. Kenfack, S. Zongouri, and H. Guedenet. 2017. "Improving Diets and Nutrition through an Integrated Poultry Value Chain and Nutrition Intervention (SELEVER) in Burkina Faso: Study Protocol for a Randomized Trial." Trials 18(1): 412.
46. Gender at Work. n.d. "Gender at Work Framework." https://genderatwork.org/analytical-framework/
47. Ghosh, A., and D. Chopra. 2019. "Paid Work, Unpaid Care Work and Women's Empowerment in Nepal." Contemporary South Asia 27(4): 471–85.
48. Ghosh, S., and D. Vinod. 2017. "What Constrains Financial Inclusion for Women? Evidence from Indian Micro Data." World Development 92(April): 60–81.
49. Gilligan, D., N. Kumar, S. McNiven, J. Meenakshi, and A. Quisumbing. 2020. "Bargaining Power, Decision Making, and Biofortification: The Role of Gender in Adoption of Orange Sweet Potato in Uganda." Food Policy 95 (June): 101909.
50. Grabe, S. 2010. "Promoting Gender Equality: The Role of Ideology, Power, and Control in the Link Between Land Ownership and Violence in Nicaragua." Analyses of Social Issues and Public Policy 10(1): 146–70.
51. Grabe, S., R. Grose, and A. Dutt. 2014. "Women's Land Ownership and Relationship Power: A Mixed Methods Approach to Understanding Structural Inequities and Violence against Women". Psychology of Women Quarterly 39(1): 7–19.
52. Grabowski, P.P., I. Djenontin, L. Zulu, J. Kamoto, J. Kampanje-Phiri, A. Darkwah, I. Egyir, and G. Fischer. 2020. "Gender- and Youth-Sensitive Data Collection Tools to Support Decision Making for Inclusive Sustainable Agricultural Intensification." International Journal of Agricultural Sustainability. https://doi.org/10.1080/14735903.2020.1817656
53. Gutierrez-Montes, I., M. Arguedas, F. Ramirez-Aguero, L. Mercado, and J. Sellare. 2020. "Contributing to the Construction of a Framework for Improved Gender Integration into Climate-Smart Agriculture Projects Monitoring and Evaluation: MAP-Norway Experience." Climatic Change 158(1): 93–106.
54. Gupta, S., P.L. Pingali, and P. Pinstrup-Andersen. 2017. "Women's Empowerment in Indian Agriculture: Does Market Orientation of Farming Systems Matter?" Food Security 9(6): 1447–63.
55. Halbrendt, J., A.H. Kimura, S.A. Gray, T. Radovich, B. Reed, and B.B. Tamang. 2014. "Implications of Conservation Agriculture for Men's and Women's Workloads Among Marginalized Farmers in the Central Middle Hills of Nepal." Mountain Research and Development 34(3): 214–22.
56. Harris, J., W. Tan, B. Mitchell, and D. Zayed. 2021. "Equity in Agriculture-Nutrition-Health Research: A Scoping Review." Nutrition Reviews. https://doi.org/10.1093/nutrit/nuab001
57. Heckert, J., D.K. Olney, and M.T. Ruel. 2019. "Is Women's Empowerment a Pathway to Improving Child Nutrition Outcomes in a Nutrition-Sensitive Agriculture Program? Evidence from a Randomized Controlled Trial in Burkina Faso." Social Science & Medicine 233 (July): 93–102.
58. Hillenbrand, E., N. Karim, P. Mohanraj, and D. Wu. 2015. "Measuring Gender-Transformative Change: A Review of Literature and Promising Practices." Working Paper, CARE USA, Washington, DC.
59. Hoddinott, J., D. Headey, and M. Dereje. 2015. "Cows, Missing Milk Markets, and Nutrition in Rural Ethiopia." The Journal of Development Studies 51(8): 958–75.
60. Huyer, S., and S. Partey. 2020. "Weathering the Storm or Storming the Norms? Moving Gender Equality Forward in Climate-Resilient Agriculture." Climatic Change 158(1): 1–12.
61. Johnson, N., M. Balagamwala, C. Pinkstaff, S. Theis, R. Meinzen-Dick, and A. Quisumbing. 2018. "How do Agricultural Development Projects Empower Women? Linking Strategies with Expected Outcomes." Journal of Gender, Agriculture, and Food Security 3(2): 1–19.
62. Johnson, N., C. Kovarik, R. Meinzen-Dick, J. Njuki, and A. Quisumbing. 2016. "Gender, Assets, and Agricultural Development: Lessons from Eight Projects." World Development 83(July): 295–311.
63. Johnston, D., S. Stevano, H. Malapit, E. Hull, and S. Kadiyala. 2015. "Agriculture, Gendered Time Use,

and Nutritional Outcomes: A Systematic Review." IFPRI Discussion Paper 01456, International Food Policy Research Institute, Washington, DC.
64. Jost, C., F. Kyazze, J. Naab, S. Neelormi, J. Kinyangi, R. Zougmore, P. Aggarwal, G. Bhatta, M. Chaudhury, M. Tapio-Bistrom, S. Nelson, and P. Kristjanson. 2016. "Understanding Gender Dimensions of Agriculture and Climate Change in Smallholder Farming Communities." Climate and Development 8(2): 133–44.
65. Kabeer, N. 1999. "Resources, Agency, Achievements: Reflections on the Measurement of Women's Empowerment." Development and Change 30(3): 435–464.
66. Kabeer, N. 2017. "Economic Pathways to Women's Empowerment and Active Citizenship: What Does the Evidence from Bangladesh Tell Us?" The Journal of Development Studies 53(5): 649–663.
67. Kabir, M.S., M.R. Marković, and D. Radulović. 2019. "The Determinants of Income of Rural Women in Bangladesh." Sustainability 11(20): 5842.
68. Kantor, P., and F. Kruijssen, F. 2014. "Informal Fish Retailing in Rural Egypt: Opportunities to Enhance Income and Work Conditions for Women and Men." WorldFish, Penang, Malaysia.
69. Karmacharya, C., K. Cunningham, J. Choufani, and S. Kadiyala. 2017. "Grandmothers' Knowledge Positively Influences Maternal Knowledge and Infant and Young Child Feeding Practices." Public Health Nutrition 20(12): 2114–23.
70. Kassie, M., M. Fisher, G. Muricho, and G. Diiro. 2020. "Women's Empowerment Boosts the Gains in Dietary Diversity from Agricultural Technology Adoption in Rural Kenya." Food Policy 95 (August): 101957.
71. Kawarazuka, N., C. Locke, C. McDougall, P. Kantor, and M. Morgan. 2017. "Bringing Analysis of Gender and Social–Ecological Resilience Together in Small-Scale Fisheries Research: Challenges and Opportunities." Ambio 46(2): 201–13.
72. Khoza, S., D. Van Niekerk, and L.D. Nemakonde. 2019. "Understanding Gender Dimensions of Climate-Smart Agriculture Adoption in Disaster-Prone Smallholder Farming Communities in Malawi and Zambia." Disaster Prevention and Management: An International Journal 28(5): 530–47.
73. Kimambo, J., M.M. Kavoi, J. Macharia, and N. Nenguwo. 2018. "Assessment of Factors Influencing Farmers' Nutrition Knowledge and Intake of Traditional African Vegetables in Tanzania." African Journal of Food, Agriculture, Nutrition and Development 18(2): 13353–13371.
74. Kiptot, E., and S. Franzel. 2012. "Gender and Agroforestry in Africa: A Review of Women's Participation." Agroforestry Systems 84(1): 35–58.
75. Komatsu, H., H.J.L. Malapit, and S. Theis. 2018. "Does Women's Time in Domestic Work and Agriculture Affect Women's and Children's Dietary Diversity? Evidence from Bangladesh, Nepal, Cambodia, Ghana, and Mozambique." Food Policy 79(August): 256–270.
76. Kosec, K., C.H. Mo, E. Schmidt, and J. Song. 2021. "Perceptions of Relative Deprivation and Women's Empowerment." World Development 138 (February): 105218.
77. Kristjanson, P., E. Bryan, Q. Bernier, J. Twyman, R. Meinzen-Dick, C. Kieran, C. Ringler, C. Jost, and C. Doss. 2017. "Addressing Gender in Agricultural Research for Development in the Face of a Changing Climate: Where Are We and Where Should We Be Going?" International Journal of Agricultural Sustainability 15(5): 482–500.
78. Kruijssen, F., C. McDougall, and I. van Asseldonk. 2018. "Gender and Aquaculture Value Chains: A Review of Key Issues and Implications for Research." Aquaculture 493(1): 328–337.
79. Kruijssen, F., S. Rajaratnam, A. Choudhury, C. McDougall, and J.P.T. Dalsgaard. 2016. "Gender in the Farmed Fish Value Chain of Bangladesh: A Review of the Evidence and Development Approaches." Program Brief: 2016-38. Penang, Malaysia: WorldFish.
80. Kumar, N., K. Raghunathan, A. Arrieta, A. Jilani, S. Chakrabarti, P. Menon, and A.R. Quisumbing. 2019. "Social Networks, Mobility, and Political Participation: The Potential for Women's Self-Help Groups to Improve Access and Use of Public Entitlement Schemes in India." World Development 114(February): 28–41.
81. Lambrecht, I., and K. Mahrt. 2019. "Gender and Assets in Rural Myanmar: A Cautionary Tale for the Analyst." IFPRI Discussion Paper 01894, International Food Policy Research Institute, Washington, DC.
82. Lees, S., N. Kyegombe, A. Diatta, A. Zogrone, S. Roy, and M. Hidrobo. 2021. "Intimate Partner Relationships and Gender Norms in Mali: The Scope of Cash Transfers Targeted to Men to Reduce Intimate Partner Violence." Violence Against Women 27(3–4): 447–469.
83. Leight, J. 2021. "Like Father, like Son, like Mother, like Daughter: Intergenerational Transmission of Intrahousehold Gender Attitudes in Ethiopia." World Development 142(June): 105359.
84. Lentz, E., S. Narayanan, and A. De. 2019. "Last and Least: Findings on Intrahousehold Undernutrition from Participatory Research in South Asia." Social Science & Medicine 232(July): 316–323.
85. Liverpool-Tasie, L., A. Wineman, S. Young, J. Tambo, C. Vargas, T. Reardon, G. Adjognon, J. Porciello, N.

Gathoni, L. Bizikova, A. Gaile, and A. Celestin. 2020. "A Scoping Review of Market Links between Value Chain Actors and Small-Scale Producers in Developing Regions." Nature Sustainability 3(October): 799–808.
86. MacDonald, C.A., J. Aubel, B.A. Aidam, and A.W. Girard. 2020. "Grandmothers as Change Agents: Developing a Culturally Appropriate Program to Improve Maternal and Child Nutrition in Sierra Leone." Current Developments in Nutrition 4(1): nzz141.
87. Madzorera, I., and W. Fawzi. 2020. "Women Empowerment Is Central to Addressing the Double Burden of Malnutrition." EClinical Medicine 20(February): 100286.
88. Mahajan, K. 2017. "Rainfall Shocks and the Gender Wage Gap: Evidence from Indian Agriculture." World Development 91(March): 156–172.
89. Malapit, H.J.L., and A.R. Quisumbing. 2015. "What Dimensions of Women's Empowerment in Agriculture Matter for Nutrition in Ghana?" Food Policy 52(April): 54–63.
90. Malapit, H.J.L., E. Sraboni, A.R. Quisumbing, and A.U. Ahmed. 2019. "Intrahousehold Empowerment Gaps in Agriculture and Children's Well-Being in Bangladesh." Development Policy Review 37(2): 176–203.
91. Marimo, P., C. Caron, I. Van den Bergh, R. Crichton, E. Weltzien, R. Ortiz, and R. Tumuhimbise. 2020. "Gender and Trait Preferences for Banana Cultivation and Use in Sub-Saharan Africa: A Literature Review." Economic Botany 74(2): 226–241.
92. Meinzen-Dick, R., A. Quisumbing, C. Doss, and S. Theis. 2019. "Women's Land Rights as a Pathway to Poverty Reduction: Framework and Review of Evidence." Agricultural Systems 172(June): 72–82.
93. Meinzen-Dick, R., D. Rubin, M. Elias, A.A. Mulema, and E. Myers. 2019. "Women's Empowerment in Agriculture: Lessons from Qualitative Research." IFPRI Discussion Paper 1797, International Food Policy Research Institute, Washington, DC.
94. Meinzen-Dick, R., Q. Bernier, and E. Haglund. 2013. "The Six 'Ins' of Climate-Smart Agriculture: Inclusive Institutions for Information, Innovation, Investment, and Insurance." CAPRi Working Paper 114, International Food Policy Research Institute, Washington, DC.
95. Mishra, K., and A.G. Sam. 2016. "Does Women's Land Ownership Promote Their Empowerment? Empirical Evidence from Nepal." World Development 78(February): 360–371.
96. Montt, G., and T. Luu. 2020. "Does Conservation Agriculture Change Labour Requirements? Evidence of Sustainable Intensification in Sub-Saharan Africa." Journal of Agricultural Economics 71(2): 556–580.
97. Moore, N., C. Lane, I. Storhaug, A. Franich, H. Rolker, J. Furgeson, T. Sparling, and B. Snilstveit. 2021. The Effects of Food Systems Interventions on Food Security and Nutrition Outcomes in Low- and Middle-Income Countries. 3ie Evidence Gap Map Report 16. New Delhi: International Initiative for Impact Evaluation.
98. Moosa, C.S., and N. Tuana. 2014. "Mapping a Research Agenda Concerning Gender and Climate Change: A Review of the Literature." Hypatia 29(3): 677–694.
99. Mucioki, M., T. Johns, C. Muriithi, and G. Hickey. 2016. "The Influence of Gender Roles and Human Migrations on the Distribution of Crop Biodiversity in Tharaka, Kenya." Journal of Ethnobiology 36(1): 172–191.
100. Mudege, N.N., N. Mdege, P.E. Abidin, and S. Bhatasara. 2017. "The Role of Gender Norms in Access to Agricultural Training in Chikwawa and Phalombe, Malawi." Gender, Place & Culture 24(12): 1689–1710.
101. Mulema, A., and E. Damtew. 2016. Gender-Based Constraints and Opportunities to Agricultural Intensification in Ethiopia: A Systematic Review. ILRI Project Report. Nairobi: International Livestock Research Institute.
102. Mulmi, P., S.A. Block, G.E. Shively, and W.A. Masters. 2016. "Climatic Conditions and Child Height: Sex-Specific Vulnerability and the Protective Effects of Sanitation and Food Markets in Nepal." Economics & Human Biology 23(December): 63–75.
103. Mwaseba, D.J.B., and R. Kaarhus. 2015. "How Do Intra-Household Gender Relations Affect Child Nutrition? Findings from Two Rural Districts in Tanzania." Forum for Development Studies 42(2): 289–309.
104. Mwongera, C., K.M. Shikuku, J. Twyman, L.A. Winowiecki, E.L. Ampaire, M. Koningstein, and S. Twomlow. 2014. Rapid Rural Appraisal Report of Northern Uganda. Cali-Palmira, Colombia: International Center for Tropical Agriculture; Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
105. Naab, J.B., and H. Koranteng. 2012. "Using a Gender Lens to Explore Farmers' Adaptation Options in the Face of Climate Change: Results of a Pilot Study in Ghana." Working Paper 17. Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security.
106. Ndiritu, S., M. Kassie, and B. Shiferaw. 2014. "Are There Systematic Gender Differences in the

Adoption of Sustainable Agricultural Intensification Practices? Evidence from Kenya." Food Policy 49(1): 117–127.
107. Na, M., L. Jennings, S.A. Talegawkar, and S. Ahmed. 2015. "Association between Women's Empowerment and Infant and Child Feeding Practices in Sub-Saharan Africa: An Analysis of Demographic and Health Surveys." Public Health Nutrition 18(17): 3155–65.
108. Østergaard Nielsen, J., and A. Reenberg. 2010. "Cultural Barriers to Climate Change Adaptation: A Case Study from Northern Burkina Faso." Global Environmental Change 20(1): 142–52.
109. Niewoehner-Green, J., N. Stedman, S. Galindo, S. Russo, H. Carter, and K. Colverson. 2019. "The Influence of Gender on Rural Honduran Women's Participation and Leadership in Community Groups." Journal of International Agricultural and Extension Education 26(2): 48–63.
110. Njuki, J., E. Waithanji, B. Sakwa, J. Kariuki, E. Mukewa, and J. Ngige. 2014. "Can Market-Based Approaches to Technology Development and Dissemination Benefit Women Smallholder Farmers? A Qualitative Assessment of Gender Dynamics in the Ownership, Purchase, and Use of Irrigation Pumps in Kenya and Tanzania." IFPRI Discussion Paper 01357, International Food Policy Research Institute, Washington, DC.
111. Njuki, J. 2021. Gender Equality and Women's Empowerment in Rapidly Transforming Food Systems. 2021. Discussion Starter prepared for the United Nations Food Systems Summit 2021. https://foodsystems.community/communities/lever-of-change-gender/
112. Ouédraogo, M., P. Houessionon, R.B. Zougmoré, and S. Tetteh Partey. "Uptake of Climate-Smart Agricultural Technologies and Practices: Actual and Potential Adoption Rates in the Climate-Smart Village Site of Mali." Sustainability 11(17): 4710.
113. Parks, M.H., M.E. Christie, and I. Bagares. 2015. "Gender and Conservation Agriculture: Constraints and Opportunities in the Philippines." GeoJournal 80(1): 61–77.
114. Perez, C., E.M. Jones, P. Kristjanson, L. Cramer, P.K. Thornton, W. Förch, and C. Barahona. 2015. "How Resilient Are Farming Households and Communities to a Changing Climate in Africa? A Gender-Based Perspective." Global Environmental Change 34(September): 95–107.
115. Peterman, A., A. Quisumbing, J. Behrman, and E. Nkonya. 2011. "Understanding the Complexities Surrounding Gender Differences in Agricultural Productivity in Nigeria and Uganda." Journal of Development Studies 47(10): 1482–1509.
116. Peterman, A., J.A. Behrman, and A.R. Quisumbing. 2014. "A Review of Empirical Evidence on Gender Differences in Nonland Agricultural Inputs, Technology, and Services in Developing Countries." In Gender in Agriculture, eds. A.R. Quisumbing, R. Meinzen-Dick, T.L. Raney, A. Croppenstedt, J.A. Behrman, and A. Peterman, 145–86. Dordrecht: Springer Netherlands.
117. Picchioni, F., G. Zanello, C.S. Srinivasan, A.J. Wyatt, and P. Webb. 2020. "Gender, Time-Use, and Energy Expenditures in Rural Communities in India and Nepal." World Development 136(December): 105137.
118. Pradhan, R., R. Meinzen-Dick, and S. Theis. 2019. "Property Rights, Intersectionality, and Women's Empowerment in Nepal." Journal of Rural Studies 70 (August): 26–35.
119. Quisumbing, A., N. Kumar, and J. Behrman. 2018. "Do Shocks Affect Men's and Women's Assets Differently? Evidence from Bangladesh and Uganda." Development Policy Review 36(1): 3–34.
120. Quisumbing, A.R., K. Sproule, E.M. Martinez, and H. Malapit. 2021. "Do Tradeoffs among Dimensions of Women's Empowerment and Nutrition Outcomes Exist? Evidence from Six Countries in Africa and Asia." Food Policy 100(April): 102001.
121. Ragasa, C., H. Malapit, D. Rubin, E. Myers, A. Pereira, E. Martinez, J. Heckert, G. Seymour, D. Mzungu, K. Kalagho, C. Kazembe, J. Thunde, and G. Mswelo. 2021. "'It Takes Two': Women's Empowerment in Agricultural Value Chains in Malawi." IFPRI Discussion Paper 02006, International Food Policy Research Institute, Washington, DC.
122. Ragasa, C., N. Aberman, and C. Alvarez Mingote. 2019. "Does Providing Agricultural and Nutrition Information to Both Men and Women Improve Household Food Security? Evidence from Malawi." Global Food Security 20(March): 45–59.
123. Ragasa, C., G. Berhane, F. Tadesse, and A.S. Taffesse. 2013. "Gender Differences in Access to Extension Services and Agricultural Productivity." Journal of Agricultural Education and Extension 19(5): 437–68.
124. Ragsdale, K., M.R. Read-Wahidi, T. Wei, E. Martey, and P. Goldsmith. 2018. "Using the WEAI+ to Explore Gender Equity and Agricultural Empowerment: Baseline Evidence among Men and Women Smallholder Farmers in Ghana's Northern Region." Journal of Rural Studies 64 (November): 123–34.
125. Raghunathan, K., S. Kannan, and A.R. Quisumbing. 2019. "Can Women's Self-Help Groups Improve Access to Information, Decision-Making, and Agricultural Practices? The Indian Case." Agricultural Economics 50(5): 567–80.

126. Raghunathan, K., D. Headey, and A. Herforth. 2021. "Affordability of Nutritious Diets in Rural India." Food Policy 99(February): 101982.
127. Rakib, M., and J. Matz. 2014. "The Impact of Shocks on Gender-Differentiated Asset Dynamics in Bangladesh." Journal of Development Studies 52(3): 377–395.
128. Rakotomanana, H., D. Hildebrand, G.E. Gates, D.G. Thomas, F. Fawbush, and B.J. Stoecker. 2020. "Maternal Knowledge, Attitudes, and Practices of Complementary Feeding and Child Undernutrition in the Vakinankaratra Region of Madagascar: A Mixed-Methods Study." Current Developments in Nutrition 4(11): nzaa162.
129. Rao, N., H. Gazdar, D. Chanchani, and M. Ibrahim. 2019. "Women's Agricultural Work and Nutrition in South Asia: From Pathways to a Cross-Disciplinary, Grounded Analytical Framework." Food Policy, Special Issue: Leveraging Agriculture for Nutrition in South Asia, 82 (January): 50–62.
130. Reinbott, A., and I. Jordan. 2016. "Determinants of Child Malnutrition and Infant and Young Child Feeding Approaches in Cambodia." World Review of Nutrition and Dietetics 115: 61–67.
131. Reinbott, A., A. Schelling, J. Kuchenbecker, T. Jeremias, I. Russell, O. Kevanna, M.B. Krawinkel, and I. Jordan. 2016. "Nutrition Education Linked to Agricultural Interventions Improved Child Dietary Diversity in Rural Cambodia." British Journal of Nutrition 116(8): 1457–68.
132. Rockström, J., J. Williams, G. Daily, A. Noble, N. Matthews, L. Gordon, H. Wetterstrand, F. DeClerck, M. Shah, P. Steduto, C. de Fraiture, N. Hatibu, O. Unver, J. Bird, L. Sibanda, and J. Smith. 2017. "Sustainable Intensification of Agriculture for Human Prosperity and Global Sustainability." Ambio 46(1): 4–17.
133. Rowlands, J. 1998. Questioning Empowerment: Working with Women in Honduras. Oxford, UK: Oxfam.
134. Ruel, M., A. Quisumbing, and M. Balagamwala. 2018. "Nutrition-Sensitive Agriculture: What Have We Learned So Far?" Global Food Security 17(June): 128–153.
135. Shroff, M.R., P.L. Griffiths, C. Suchindran, B. Nagalla, S. Vazir, and M.E. Bentley. 2011. "Does Maternal Autonomy Influence Feeding Practices and Infant Growth in Rural India?" Social Science & Medicine 73(3): 447–55.
136. Sibhatu, K.T., V.V. Krishna, and M. Qaim. 2015. "Production Diversity and Dietary Diversity in Smallholder Farm Households." Proceedings of the National Academy of Sciences 112(34): 10657–10662.
137. Sraboni, E., and A. Quisumbing. 2018. "Women's Empowerment in Agriculture and Dietary Quality across the Life Course: Evidence from Bangladesh." Food Policy 81 (December): 21–36.
138. Tall, A., P.M. Kristjanson, M. Chaudhury, S. McKune, and R.B. Zougmoré. 2014. "Who Gets the Information? Gender, Power and Equity Considerations in the Design of Climate Services for Farmers." CCAFS Working Paper 89, CGIAR Research Program on Climate Change, Agriculture and Food Security, Copenhagen, Denmark.
139. Tambo, J.A., and T. Abdoulaye. 2012. "Climate Change and Agricultural Technology Adoption: The Case of Drought Tolerant Maize in Rural Nigeria." Mitigation and Adaptation Strategies for Global Change 17(3): 277–92.
140. Teeken, B., O. Olaosebikan, J. Haleegoah, E. Oladejo, T. Madu, A. Bello, E. Parkes, C. Egesi, P. Kulakow, H. Kirscht, and H.A. Tufan. 2018. "Cassava Trait Preferences of Men and Women Farmers in Nigeria: Implications for Breeding." Economic Botany 72(3): 263–77.
141. Theis, S., E. Bryan, and C. Ringler. 2019. "Addressing Gender and Social Dynamics to Strengthen Resilience for All." In 2019 Annual Trends and Outlook Report: Gender Equality in Rural Africa: From Commitments to Outcomes, eds. A.R. Quisumbing, R.S. Meinzen-Dick, and J. Njuki, 126–139. Washington, DC: International Food Policy Research Institute.
142. Theriault, V., M. Smale, and H. Haider. 2017. "How Does Gender Affect Sustainable Intensification of Cereal Production in the West African Sahel? Evidence from Burkina Faso." World Development 92(April): 177–91.
143. Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. "Global Food Demand and the Sustainable Intensification of Agriculture." Proceedings of the National Academy of Sciences 108(50): 20260–20264.
144. Tufan, H.A., S. Grando, and C. Meola, eds. 2018. "State of the Knowledge for Gender in Breeding: Case Studies for Practitioners." Working Paper 3, CGIAR Gender and Breeding Initiative, Lima.
145. Twyman, J., M. Green, Q. Bernier, P. Kristjanson, S. Russo, A. Tall, E. Ampaire, M. Nyasimi, J. Mango, S. McKune, C. Mwongera, and Y. Ndourba. 2014. "Adaptation Actions in Africa: Evidence That Gender Matters." Working Paper 83, CGIAR Research Program on Climate Change, Agriculture and Food Security, Copenhagen.
146. Uduji, J.I., E.N. Okolo-Obasi, and S.A. Asongu. 2019. "Corporate Social Responsibility and the Role of Rural Women in Sustainable Agricultural Development in Sub-Saharan Africa: Evidence from the Niger Delta in Nigeria." Sustainable Development 27(4): 692–703.

147. Vibert, E. 2016. "Gender, Resilience and Resistance: South Africa's Hleketani Community Garden." Journal of Contemporary African Studies 34(2): 252–67.
148. Wemakor, A., and H. Iddrisu. 2018. "Maternal Depression Does Not Affect Complementary Feeding Indicators or Stunting Status of Young Children (6–23 Months) in Northern Ghana." BMC Research Notes 11(1): 408.
149. Wemakor, A., and K.A. Mensah. 2016. "Association between Maternal Depression and Child Stunting in Northern Ghana: A Cross-Sectional Study." BMC Public Health 16(1): 869.
150. Wiig, H. 2013. "Joint Titling in Rural Peru: Impact on Women's Participation in Household Decision-Making." World Development 52(December): 104–19.
151. Wolf, K., and M. Frese. 2018. "Why Husbands Matter: Review of Spousal Influence on Women Entrepreneurship in Sub-Saharan Africa." Africa Journal of Management 4 (January): 1–32.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
IFPRI

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

THE FUTURE OF SMALL FARMS: INNOVATIONS FOR INCLUSIVE TRANSFORMATION

by Xinshen Diao, Thomas Reardon, Adam Kennedy, Ruth S. DeFries, Jawoo Koo, Bart Minten, Hiroyuki Takeshima and Philip Thornton

INTRODUCTION

By 2050, the United Nations projects that 68 percent of the world population will live in cities (UN DESA 2019). However, with continuous population growth, the number of people living in rural areas of many low- and middle-income countries (LMICs) will continue to rise. Two-thirds of the extreme poor live in rural areas (World Bank 2016) and the livelihoods of two to three billion rural people, often the most food inse-

ABOUT THE AUTHORS

Xinshen Diao, Deputy Division Director International Food Policy Research Institute (IFPRI)

Thomas Reardon, Distinguished Professor, Michigan State University

Adam Kennedy, Senior Program Manager, International Food Policy Research Institute (IFPRI)

Ruth S. DeFries, Professor of Sustainable Development, Columbia University

Jawoo Koo, Senior Research Fellow, International Food Policy Research Institute (IFPRI)

Bart Minten, Senior Research Fellow, International Food Policy Research Institute (IFPRI)

Hiroyuki Takeshima, Senior Research Fellow, International Food Policy Research Institute (IFPRI)

Philip Thornton, Senior Scientist, International Livestock Research Institute (ILRI)

cure and vulnerable, still depend primarily on small farms (Laborde, Parent, and Smaller 2020; Woodhill, Hasnain, and Griffith 2020).

There are various estimates of the number of small farms in the world, but they all suggest these farms are numerous. Lowder et al. (2016) used agricultural census data from 167 countries to estimate that, of the total 570 million[1] farms in the world, 475 million farms have less than 2 hectares (ha), dominating agriculture in most LMICs, where farm sizes continue to fall. Africa south of the Sahara has the highest rural population growth rate globally, and thus the number of small farms is expected to increase more than in other regions. Africa's share of total world rural poverty is also expected to rise from 39.6 percent in 2015 to 58.1 percent in 2050 (Thurlow, Dorosh, and Davies 2019). Transforming Africa's agriculture sector is thus a priority embodied in the Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods (AU 2014). However, to meet the Malabo goals and achieve multiple SDGs in all LMICs by 2030, creating an enabling environment where small farms are included in and benefit from rapid growth and transformation of agrifood systems is urgent (Barrett et al. 2020).

Small farms not only contribute to feeding the households that operate them but also make two broader contributions. First, small farms are important to the overall food security of LMICs. Samberg et al. (2016) noted that farms less than 5 ha are responsible for 53 percent of the global production of food calories for human consumption. Herrero et al. (2017) reported that in Africa and South and Southeast Asia small farms with less than 2 ha produce around 30 percent of food and make valuable contributions to micronutrient-rich food production. Ricciardi et al. (2018) estimated that farms under 2 ha globally produce 30–34 percent of the food supply. Nonetheless, small farm households themselves are often unable to afford a nutritious diet (Bai et al. 2020).

Second, small farms contribute to the sustainability of agrifood systems by maintaining the genetic diversity of crops and livestock and supporting ecosystem services. Small farms have more crop diversity and harbor greater non-crop biodiversity at the farm and landscape scales than do larger farms (Ricciardi et al. 2021). Subsistence-oriented small farmers plant a greater diversity of traditional crops and maintain genetic resources by cultivating land races (Fifanou et al. 2011; McCord et al. 2015). Small fields have more edges than larger fields, creating a heterogeneous landscape and providing habitat for non-crop species (Ouin and Birel 2002). To the extent that small farms have more tree cover than larger farms, they provide above- and below-ground carbon storage, with global benefits for climate mitigation (Ritchie and Roser 2017). Trees on farms can also improve water infiltration, a hydrological service that benefits other water users in the landscape and downstream (Anache et al. 2019).

For small farms to be part of inclusive and sustainable agrifood system transformation, both innovative technology and market institutions are required to support LMICs' diverse agroecological and socioeconomic contexts. Many debates on the future of small farms focus only on farm production, rather than the whole context of farm household livelihoods, which include off-farm activities, or the agrifood system on which farms depend for buying inputs and selling outputs (Reardon et al. 2019; Giller et al. 2020). The future of small farms should instead be assessed using a holistic livelihoods and agrifood system lens.

WHO ARE SMALL FARMERS IN THE FUTURE?

More than 410 million farms are very small, with less than 1 ha of land, and another 70 million are between 1 and 2 ha (Lowder et al. 2016). However, discussions of farm size often ignore land quality considerations (Eastwood, Lipton, and Newell 2010). For example, a 5-ha farm in a rainfed zone with poor quality soil may support less production than a 1 ha farm in an irrigated zone with good soil. Thus, mere farm size ranges tell us nothing about differences in agroecological land quality, or about the socioeconomic contexts in which they operate, such as market and infrastructural conditions (FAO 2014; Graueb et al. 2016). While the product mix of small farm varies depending on this context, many are diversifying that mix, driven by urbanization, consumers' dietary preferences, technology, infrastructure development, and rural-urban links. Moreover, households that operate small farms tend to have diversified income sources, including non-farm activities, and that diversification is expected to increase over time, although at different rates among

1 Hickson and Thornton (2020) updated the total to 590 million farms, which probably increases the total of small farms above the Lowder et al. (2016) estimate.

different sets of small farmers (Davis, Giuseppe, and Zezza 2017).

Despite the strong heterogeneity across small farms, they can be categorized in ways that make our analysis more tractable. Following Vorley (2002), Dorward et al. (2009), Hazell and Rahman (2014), and Hazell et al. (2017) and based primarily on Hazell (2019), we classify small farmers in LMICs into three groups.

Commercial small farmers run their farms as businesses. While commercial agriculture is an important source of income for them, many also undertake rural non-farm employment (RNFE). Most commercial small farmers do not specialize in high-value crops or livestock, as many also produce food crops. Their product and activity mix are conditioned by agroecological circumstances, urban market proximity, rural infrastructure, and the agro-processors, logistics, exporters, and wholesale enterprise investment and density in their area. Climate change and economic transformation also condition their farm businesses and will create new challenges and opportunities even over the next 10 years. Some commercial small farms will continue to focus on today's traditional export crops—for example, cocoa in Ghana, cotton in Mali, and coffee in Ethiopia—while increasing numbers will turn to products that cater to the diversifying diets of burgeoning domestic urban markets, including fruits, vegetables, fish, poultry, edible oils, milk, and feed grains such as soy. Non-cereal products are especially labor-demanding and often offer little or no economies of scale, allowing small farms to be competitive. Over time we expect to see greater specialization in the farming of high-value products and a movement away from the combination of cash and staple crop farming, similar to what one sees among specialized vegetable farmers in the Shandong province of China (Huang, Gong, and Huang 2010) or specialized poultry and pig farmers near Yangon in Myanmar (Belton et al. 2020).

Small farmers in transition often depend heavily on RNFE while also maintaining small plots for home food consumption plus some semi-commercialized food or non-food products. They tend to buy a substantial share of their food. These farmers are in zones where favorable non-farm opportunities exist locally or in near-by towns. With demand growing for high-value farm products in cities, some transitional farmers will commercialize their small farms while continuing their RNFE. However, others may exit agriculture or maintain just small food plots because access to food markets in their area is uncertain, or because the RNFE labor market itself is uncertain or limited (de Janvry and Sadoulet 2006). Thus, many small farmers in this group will continue to have one foot in farming and one foot in RNFE as their major source of income, and their number is expected to remain large over the next decade.

Subsistence-oriented small farmers are marginalized for a variety of reasons, many of which will be difficult to change in the next decade, such as ethnic discrimination, sickness, age, or their farm's location in a remote area with limited agricultural potential. We expect the number of these small farms to fall with economic transformation, but it is unrealistic to expect most will disappear in the next decade. These farm households tend to undertake some RNFE or farm wage labor (usually the domain of the poorest farmers or the landless), but many of the same factors that constrain their farming also prevent them from undertaking remunerative RNFE to become transition farmers. These subsistence-oriented farmers are typically net buyers of staple foods. While market and technology development will help them improve farm productivity, the above constraints limit even this. They need social protection policies and other public support beyond what the agrifood system and rural labor market can provide.

RNFE is an important income source for rural small farm households and on average occupies more of their working time than farming in many African and Asian LMICs (Dolislager et al. 2020). For commercialized and transition small farmers, who are often in places with favorable agroclimates and adequate infrastructure, RNFE helps fund farming by providing cash or collateral for credit to buy inputs and diversifying income risk from agriculture. This can incentivize experimentation with new production technologies and riskier products like vegetables, poultry, and fish that have higher values. Increases in local RNFE activities often lead to rising rural wages (Murgai and Lanjouw 2009), which can induce the adoption of mechanization (Wang, Yamauchi, and Huang 2016). However, in less favorable agroclimatic zones or hinterland areas where most subsistence-oriented small farmers are located, RNFE is used mainly to fund food purchases and competes with, but also compensates for, unprofitable farming (Davis et al. 2009).

INNOVATIONS FOR THE FUTURE OF SMALL FARMS

The future of small farms will depend on technological and institutional innovations that are now appearing in some developed and developing county contexts or have yet to be developed (Herrero et al. 2021, 2020). Technological innovations have the potential to benefit small farms in LMICs, but ensuring their appropriateness remains a challenge. High transaction costs, lack of collective action, and failures in production and marketing coordination all introduce risks for small farms and are commonly seen as barriers to adopting modern technologies and participating in value chains. Many subsistence farmers may be too remote from markets or lack the capacity to benefit from new technologies. Transition farmers can be disincentivized from adopting new technologies if they are labor-intensive and compete with their non-farm employment. Even for commercial small farmers, the adoption of new technologies requires enabling conditions from output and input supply chains. Small farmers' adoption of new technologies and the cultivation of higher-value products thus requires that they have the proper profit incentives and market access, which are in large part a function of the broad market institutional context. Effective market institutions require improved infrastructure that facilitates input supply chains upstream from the farm and connects small farmers to cities downstream from their farms.

Downstream from the farm, output market conditions affect small farmers' prices, risk, and transaction costs. Critical factors include urban market size and proximity; the density and quality of roads between farmers and markets; and the midstream (wholesalers, logistics firms, and processors) and downstream (retailers) accessibility to and conduct toward small farmers. Developments in these enabling conditions in LMICs are themselves local innovations, which often rapidly improve market access for small farmers, as in the examples from Ethiopia, Nigeria, and India discussed below. Changes in these conditions will continue to be the main factor affecting small farmers' technology adoption, income growth, and inclusion in agrifood system transformation in the next decade. Some emerging technologies, such as e-commerce linked to digitalization, are also promising innovative market institutions that will impact the relationship between small farmers and markets in the next few decades.

The urban market now makes up the largest share of national food consumption in LMICs (Reardon et al. 2019). Proximity to urban markets in primary and secondary cities and small towns asserts a strong influence on market conditions and the technology and product choices of small farmers (Vandercasteelen et al. 2018). Highways and rural roads connecting farmers to urban markets likewise are critical to small farmers' access to these booming urban markets, suggesting the importance of public investment in rural infrastructure (Stifel, Minten, and Koru 2016).

The combination of growing urban markets, expanding road connections, and the development of wholesale markets provides favorable conditions for the spontaneous formation of clusters of wholesalers, cold storages, processors, and logistics enterprises that provide crucial services that enable small farmers to access urban markets. The emergence of clusters of small and medium enterprises (SMEs) offering potato cold storages in Bihar, India, is a good example; these have allowed small farmers to store their produce and wait for much higher prices in the off-season (Minten et al. 2014). In Ethiopia, the spontaneous development of a teff value chain connecting rural areas to Addis Ababa has been facilitated by the growth of midstream private SMEs utilizing public infrastructure and improvements in wholesale markets. Midstream market development also spurred the adoption of new technology and a new teff variety by small farmers (Minten et al. 2016). Many thousands of small chicken farmers in Nigeria, mostly women, benefited from the rapid growth of long north–south maize supply chains, operated by thousands of SME wholesalers and feed millers, to market their chicken and eggs in towns and secondary cities (Liverpool-Tasie et al. 2017). Spontaneous clusters of traders and input suppliers are also seen in aquaculture districts of Bangladesh and are a key determinant of small farmer technology adoption (Hu et al. 2019).

The relations of supply chain firms with small farmers are a critical determinant of small farmers' participation in markets for high-value agricultural products. These firms not only buy from small farms but also often provide resources and services that small farmers need to participate in the market, from inputs and credit to adopt new technologies that meet market requirements to services such as aggregating, sorting, and packing. This facilitation is offered through formal contract-farming arrangements with large processors and retailers (Swinnen and Kuijpers 2018) as well as through informal relationships with SME wholesalers and processors that reduce the price risk for small farms (Liverpool-Tasie et al. 2020). Relative to the "traditional" arrangement of spot markets, this facilitation can be broadly seen as a market institution innovation, especially in the poorer LMICs. We expect these relationships to expand over the next decade as the double-pronged food system revolution continues its rapid course, with both the proliferation of SMEs and of modern large-scale firms underpinning the growth of rural-urban supply chains (Reardon et al. 2019).

Despite still being in its infancy in LMICs, e-commerce (marketing online) and e-procurement (buying intermediate inputs online) are emerging rapidly. The diffusion of Internet access, mobile phones, and computers helps the spread of “delivery intermediaries,” whose expansion has been particularly rapid during the COVID-19 pandemic as consumers tried to avoid in-person shopping (Reardon and Swinnen 2020). COVID-19 accelerated e-commerce growth, for example, from 30 to 70 percent per year in India, 10 to 20 percent in China, and 20 to 50 percent in Nigeria (Vardhan 2020). The benefits of e-commerce for small farmers will depend on three conditions. First, widespread access to e-commerce will depend on mobile phone rates and Internet costs, which currently are particularly high in Africa (Torero 2019). Second, while e-commerce can make it easier for small farmers to sell to urban markets, their costs and product quality must still be competitive with medium and large farmers and importers. Small farmers linked to e-commerce may be better able to compete in more proximate niche markets. Third, e-commerce as digitalization per se only informs a buyer of a seller and a seller of a buyer; the final transaction still relies on delivery intermediaries, roads, and logistics, and the same high transaction costs that have constrained the development of non-digitized supply chains will constrain large numbers of small farmers from participating in e-commerce.

Encouragingly, there are interesting examples of e-commerce that are inclusive of small farmers with potential to spread in the future, depending on the three conditions noted above. In Indonesia, the Rumah Sayur Group, a vegetable farm co-op with 2,500 farmers, sold to supermarkets, wet markets, and food-service businesses in Jakarta before the pandemic. During the pandemic, they turned to Alibaba’s Lazada to sell directly to consumers and retailers. In Malaysia, Lazada connected SME flower suppliers to online florists to gain a new customer base when COVID-19-related restrictions interrupted the traditional marketing system (Harper 2020). In Africa, Facebook and other e-platforms have helped small farmers sell directly to consumers. Examples include Koop direk von boer (buy directly from the farmer), a Facebook group of farmers created in May 2020 that attracted 46,000 members across South Africa in just two weeks (Masiwa 2020).

Upstream from the farm, market conditions affect the input prices, risk, and transaction costs facing small farmers. Just as the output market affects the profitability of adopting new farm technologies and the transition to higher-value products, as do input supply chains. Importantly, input market conditions are parallel to output market conditions, affected by many of the same policies and public investments discussed in the context of downstream factors. Again, the development of these conditions is a local innovation. Changes in these conditions can rapidly improve input market access for small farmers, spurring technology change at farm level.

Some particularly interesting market institution and technological innovations in agricultural services markets appear to be helping small farmers. We characterize them as the development of **mobile “outsource” services**. They include a wide range of services available to farmers on a fee basis. For an individual small farmer, the outlays of capital for machines required would not be affordable given their small scale and the large lump-sum fixed cost for machinery. Such on-demand operational services emerged in the United States and European countries in the early 1880s where large farmers dominated. Small farmer demand for mechanization and agricultural operational services has risen in recent years in LMICs, first in Asia and Latin America and more recently in Africa. These services, perhaps especially as they are facilitated by communications innovations, appear to provide important support to small farming technological change. In general, mobile technology can help service supply and extension reach widely dispersed small farmers (Van Campenhout, Spielman, and Lecoutere 2021). For example, mobile mechanization services for land preparation, harvesting, and threshing are hired by many small farmers in South and Southeast Asia (Zhang, Yang, and Reardon 2017; Paudel et al. 2019; Diao, Takeshima, and Zhang 2020; Yagura 2020; Belton et al. 2021). They are increasingly accessible for small farmers in Africa (Berhane et al. 2017; Kahan, Bymolt, and Zaal 2018; Takeshima et al. 2018; Diao, Takeshima, and Zhang 2020; Cabral 2021). Mobile phones are widely used for connecting service providers and small farmers, and new digital platforms appear to have potential to reach groups of small farmers. Examples include Hello Tractor in Nigeria, TroTro Tractor in Ghana, Rent to Own in Zambia, and EM3, Trringo, and farMart in India (Birner et al. 2021; Daum et al. 2020).

Moreover, other SME services are emerging in various agricultural operations traditionally done by small farmers themselves, such as for rice seeding and transplanting in southern China (Li et al. 2015; Gong et al. 2012); spraying, pruning, land preparation, harvesting, and marketing for mango farmers in Indonesia (Qanti et al. 2017); seed propagation, digging wells and ponds, spraying, and loading trucks for vegetable farmers in Ethiopia (Minten et al. 2020); and bee pollination services for vegetable and fruit growers in China (Altay News 2019). Many of these services have replaced labor-intensive farming activities with machines or specialized techniques, helping small farmers who lack the cash to invest in machines, the skills to use machines and other techniques, or simply the time to spend farming because of non-farm employment. These services also introduce small farmers to new technologies that they otherwise might have been unaware of had they not been provided as part of a package of services by SMEs, such as flower hormone use to extend harvesting of mangoes in Indonesia (Qanti et al. 2017).

New institutional innovations can also benefit small farmers through contributions to **sustainable land stewardship**. Market-based institutions that incentivize farmers to maintain ecosystem services and biodiversity have been used for over a decade. With payments for ecosystem services (PES), the private or public sector pays land stewards (farmers) to protect watersheds, sequester carbon through tree planting, or conserve biodiversity (Milder, Scherr, and Bracer 2010). In the case of carbon, for example, the institution providing payments receives offset credits in the voluntary or regulatory carbon market. Another scheme involves certification of agricultural commodities, such as coffee, palm oil, and cacao. Certification schemes are generally implemented by non-governmental organizations (NGOs) and rely on consumers paying a premium for production practices that conform to sustainable social and environmental goals (Brandi et al. 2015; Giovannucci and Ponte 2005; Ruysschaert and Salles 2014). Smallholder farmers have benefited from these schemes only to a modest degree due to high transaction costs, low demand for ecosystem services, and poor access to information.

For carbon markets, smallholder participation is impeded by the required technical capacity as well as the costs of monitoring and complex requirements for reporting (Brandi et al. 2015; Wells et al. 2017). With certification schemes, evidence indicates mixed success for environmental, social, and economic goals. The supply of certified products is generally larger than the demand (DeFries et al. 2017). Insecure land tenure, lack of credit, and insufficient profit to warrant the required investments hamper smallholder participation in both PES and certification schemes.

With rising recognition of the importance of land stewardship for climate mitigation and conservation of biodiversity, institutions to incentivize protection of ecosystems services and sustainability goals are likely to become more widespread in the coming decades. Carbon markets, which to date have largely been unable to stem land clearing and greenhouse-gas-emitting practices on agricultural land, will likely be a more significant driver of farmers' decisions in the future. In combination with digital technology, institutional innovations have potential to reduce transaction costs and enable participation by smallholders to maximize their ability to benefit from these schemes, both to boost their incomes and contribute to society's sustainability goals. Technology and training for smallholders to access and interpret satellite data, monitor their lands, and fulfill reporting requirements are needed if they are to benefit from a growing demand for ecosystem services.

POLICIES FOR INCLUSIVE SMALL FARM TRANSFORMATION THROUGH INNOVATION

This brief has sought to imagine the future of small farms and identify promising innovations in agrifood systems to improve their prospects over the next 10 years. Because small farms are heterogeneous and dynamic, we classed them into three groups: commercial, in-transition, and subsistence-oriented small farms. Each has its own set of challenges and opportunities, and policies and investments that prioritize inclusive small farm transformation must be differentiated to best target the needs of each group as agrifood systems evolve (Hazell 2019).

Commercial small farmers are the vanguard of agrifood transformation and best prepared to take advantage of the opportunities that growing market demand for agrifood products will create. They tend to be located in more favorable agroclimates, nearer to cities and towns, and in areas better served by infrastructure and midstream SMEs that facilitate input and output markets. These same market opportunities will incentivize some transitional farmers to invest in their small farms to become commercial farmers. **To enhance small commercial and transitional farmers' competitiveness to pursue these market opportunities, government policies and public investments in the following areas are important:**

- Increase investments in infrastructure, including rural roads connecting to secondary and tertiary cities, that can create economies of agglomeration and a critical mass of proximate services such as wholesale, logistics, and farm input provision for small farmers in the surrounding rural areas, thus reducing transaction costs. Often mobile agricultural services are clustered in towns and fan out to serve small farms in a hub-and-spoke model (Zhang et al. 2017). Many new digital technologies applied in e-commerce, information provision, and farm service businesses also depend on good infrastructure. While initial investments need to come from

government, they will serve to crowd in private investments from both large companies and SMEs.
- Promote education and training programs that target rural youth to develop the skills and knowledge required to support modern agriculture and marketing. These skills are necessary for both farm management and for off-farm jobs in logistics, machinery maintenance/repair services, and broader RNFE.
- Facilitate co-operatives and farmer groups that can collectively pursue emerging opportunities in urban markets and modern farm technology. Local networks can also be strengthened through village-level innovation platforms to link smallholder farmers with extension and research, such as China's Science and Technology Backyard (Barrett et al. 2020). These show promise for drawing together the wisdom of (small farmer) crowds with the knowledge of cutting-edge scientific researchers to accelerate discovery, adaptation, and diffusion (Nelson, Coe, and Haussmann 2019; van Etten et al. 2019).
- Support SMEs upstream and downstream from farms by reducing unnecessary regulations and informal restrictions that often discourage SME development. SMEs are more accessible to small farmers than larger enterprises, and small farmers value the mix of services that SMEs provide (Liverpool-Tasie et al. 2020).

RNFE is the main economic activity of transitional farmers and is increasingly the main source of income for most small farmers. RNFE provides small farmers with cash both to purchase food and for farm investments to raise productivity, expand commercial activities, and produce higher-value products. RNFE is also important for some marginalized farmers, helping them reduce their reliance on risky, low-yield agriculture. For these farmers, RNFE development will directly improve food security in a way that marginally boosting agricultural production cannot (ZEF and FAO 2020; Frelat 2016). Public investments and policies that facilitate growth of the agrifood system must pay more attention to creating enabling environments for the development of RNFE and strengthening the synergy between agriculture and RNFE in rural areas. In this regard, the following actions are promising for **governments to actively promote agriculture–RNFE synergies for rural development and agrifood system transformation:**

- Pursue policies that have broad effects across economic activities in rural areas and do not limit interventions to farming alone. RNFE and farming are complementary, and both are needed for inclusive growth in rural areas.
- Develop an enabling environment—including basic infrastructure, property rights, and legal systems with enforcement mechanisms—favorable to rural businesses that encourage and facilitate inclusive RNFE (Haggblade, Hazell, and Reardon 2007).
- Identify engines of regional growth through consultation with the private sector and farmers, and conduct supply chain diagnostics for prioritization of strategic interventions (Haggblade et al. 2007). Emphasize differentiated strategies and flexible institutional coalitions for implementation appropriate to diverse rural areas.

This brief emphasizes the importance of market institution innovations for achieving higher agricultural productivity and quality through small farm technology adoption and improving incomes for small farm households through participation in both farm and non-farm economic activities. In addition to the policy recommendations discussed above, some **additional policy recommendations** are listed here, although adapting and differentiating policies over heterogeneous contexts across LMICs requires context-specific research and consultation with stakeholders (Barrett 2020):

- Support new technologies that reduce risk and are attractive to small farmers when viewed in a holistic way, taking into account farmers' resource environment as well as their livelihood strategies. Do not automatically assume labor-intensive innovations are appropriate for small farmers, who often want to reduce, not intensify, their farm labor use (Hazell 2019). For transitional farmers who depend on RNFE, proposing new labor-intensive farming activities could fail if they cut into the time farmers have available for RNFE livelihood strategies (Moser and Barrett 2006).
- Ensure that agricultural interventions to support sustainable farming practices are economically viable for farmers and provide direct economic benefits. In the longer term, farmers are most strongly motivated to adopt and maintain sustainable practices when they perceive positive outcomes of these practices for their farm or the environment (Piñeiro et al. 2020).
- Scale up productive social protection programs for subsistence farmers in hinterland areas who face barriers in accessing markets and other economic opportunities. Safety net programs ease liquidity constraints and increase tolerance for risk among small farms and, when integrated with measures to increase agricultural productivity, have potential to make significant progress toward the eradication of hunger (Wouterse et al. 2020).

REFERENCES

1. Altay News. 2019."Shu Xinanda: 'Visit Huiju' Task Force Asked Bees to Work to Spread Pollination to Promote Income." August 14. https://baijiahao.baidu.com/s?id=1641857490903640521&wfr=spider&for=pc (in Chinese).
2. Anache, J. A. A., E. Wendland, L.M.P. Rosalem, C. Youlton, and P.T.S. Oliveira. 2019. "Hydrological Trade-Offs Due to Different Land Covers and Land Uses in the Brazilian Cerrado." Hydrology and Earth System Sciences 23(3): 1263–1279.
3. Arslan, A., K. Floress, C. Lamanna, L. Lipper, S. Asfaw, and T. Rosenstock. 2020. The Adoption of Improved Agricultural Technologies: A Meta-Analysis for Africa. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
4. Barrett, C.B., T. Benton, J. Fanzo, M. Herrero, R.J. Nelson, E. Bageant, E. Buckler, et al. 2020. Socio-Technical Innovation Bundles for Agri-Food Systems Transformation, Report of the International Expert Panel on Innovations to Build Sustainable, Equitable, Inclusive Food Value Chains. Ithaca, NY, and London: Cornell Atkinson Center for Sustainability and Springer Nature.
5. Belton, B., A. Cho, E. Payongayong, K. Mahrt, and E. Abaidoo. 2020. "Commercial Poultry and Pig Farming in Yangon's Peri-Urban Zone." Research Paper 174. Food Security Policy Project (FSPP), Feed the Future Innovation Lab for Food Security Policy, Michigan State University. https://www.canr.msu.edu/fsp/publications/research-papers/RP_174.pdf
6. Belton, B., M. Thida Win, X. Zhang, and M. Filipski. 2021 (forthcoming). "The Rapid Rise of Agricultural Mechanization in Myanmar." Food Policy.
7. Berhane, G., K. Hirvonen, and B. Minten. 2016 "Synopsis, Agricultural Mechanization in Ethiopia: Evidence from the 2015 Feed the Future Survey." ESSP II Research Note 48. Washington, DC, and Addis Ababa, Ethiopia: International Food Policy Research Institute (IFPRI) and Ethiopian Development Research Institute (EDRI).
8. Brandi, C., T. Cabani, C. Hosang, S. Schirmbeck, L. Westermann, and H. Wiese. 2015. "Sustainability Standards for Palm Oil: Challenges for Smallholder Certification under the RSPO." The Journal of Environment & Development 24(3): 292–314.
9. Cabral, L. 2021. "Of Zinc Roofs and Mango Trees: Tractors, the State and Agrarian Dualism in Mozambique." The Journal of Peasant Studies. https://doi.org/10.1080/03066150.2020.1860026
10. Conway, G. 2011. "On Being a Smallholder." Presented at the IFAD Conference: New Directions for Smallholder Agriculture, Rome, January 25.
11. Davis, B., P. Winters, T. Reardon, and K. Stamoulis. 2009. "Rural Nonfarm Employment and Farming: Household-level Linkages." Agricultural Economics 40(2): 119–123.
12. Davis, D., S. Di Giuseppe, and A. Zezza. 2017. "Are African Households (Not) Leaving Agriculture? Patterns of Households' Income Sources in Rural Sub-Saharan Africa." Food Policy 67: 153–174.
13. De Janvry, A., and E. Sadoulet. 2006. "Making Conditional Cash Transfer Programs More Efficient: Designing for Maximum Effect of the Conditionality." World Bank Economic Review 20(1): 1–29.
14. DeFries, R., J. Fanzo, P. Mondal, R. Remans, and S. Wood. 2017. "Is Voluntary Certification of Tropical Agricultural Commodities Achieving Sustainability Goals? A Review of the Evidence." Environmental Research Letters 12(3): 033001.
15. Diao, X., H. Takeshima, and X. Zhang, eds. 2020. An Evolving Paradigm of Agricultural Mechanization Development: How Much Can Africa Learn from Asia? Washington, DC: International Food Policy Research Institute (IFPRI). https://doi.org/10.2499/9780896293809
16. Dolislager, M., T. Reardon, A. Arslan, L. Fox, S. Liverpool-Tasie, C. Sauer, and D. Tschirley. 2020. "Youth and Adult Agrifood System Employment in Developing Regions: Rural (Peri-Urban to Hinterland) vs Urban." Journal of Development Studies 57(4): 571–593.
17. Eastwood, R., M. Lipton, and A. Newell. 2010. "Farm Size." In Handbook of Agricultural Economics, Vol. 4, eds. P. Pigali and R. E. Evenson, 3323–3397. Burlington: Elsevier BV Academic Press.
18. FAO (Food and Agriculture Organization of the United Nations). 2014. The State of Food and Agriculture: Innovation in Family Farming. Rome.
19. Fifanou, V.G., C. Ousmane, B. Gauthier, and S. Brice. 2011. "Traditional Agroforestry Systems and Biodiversity Conservation in Benin (West Africa)." Agroforestry Systems 82(1): 1–13.
20. Giller, K. E., T. Delaune, J.V. Silva, K. Descheemaeker, G. van de Ven, A.G.T. Schut, M. van Wijk, J. Hammond, Z. Hochman, G. Taulya, R. Chikowo, S. Narayanan, A. Kishore, F. Bresciani, H.M. Teixeira, J. Andersson, and M. van Ittersum. 2020. The Future of Farming: Who will produce our food? Background paper for the Towards Inclusive, Sustainable, Nutritious and Efficient Food Systems project
21. Giovannucci, D., and S. Ponte. 2005. "Standards as a New Form of Social Contract? Sustainability Initiatives in the Coffee Industry." Food Policy 30(3): 284–301.
22. Gong, J., H. Zhang, Y. Hu, L. Wang, H. Long, C. Mao, H. Mao, Q. Dai, Z. Luo, K. Xui, and H. Wei. 2012.

"An Analysis on the Rising Rice Commercialized Centralized Seedling." China Rice 18(4): 26–30 (in Chinese).
23. Graeub, B.E., M. J. Chappell, H. Wittman, S. Ledermann, R. B. Kerr, and B. Gemmill-Herren. 2016. "The State of Family Farms in the World." World Development 87: 1–15.
24. Haggblade, S., P. Hazell, T. Reardon, eds. 2007. Transforming the Rural Nonfarm Economy: Opportunities and Threats in the Developing World. Washington, DC, and Baltimore: International Food Policy Research Institute and Johns Hopkins University Press.
25. Hazell, P. 2018. "Urbanization, Agriculture and Smallholder Farming." In Agriculture and Food Systems to 2050: Global Trend, Challenges and Opportunities, eds. R. Serraj and P. Pingali, 137–160. Singapore: World Scientific Publishing.
26. Hazell, P. 2020. "Importance of Smallholder Farms as a Relevant Strategy to Increase Food Security." In The Role of Smallholder Farms in Food and Nutrition Security, eds. S. Gomez y Paloma, L. Riesgo, and K. Louhichi, 29-43. Cham, Switzerland: Springer.
27. Herrero, M., P. Thornton, B. Power, J. Bogard, R. Remans, S. Fritz, J. Gerber, G. Nelson, L. See, K. Waha, R. Watson, P. West, L. Samberg, J. van de Steeg, E. Stephenson, M. van Wijk, and P. Havlík. 2017. "Farming and the Geography of Nutrient Production for Human Use: A Transdisciplinary Analysis." Lancet Planetary Health 1(1), E33–E42.
28. Herrero M., P.K. Thornton, C. Mason-D'Croz, J. Palmer, T.G. Benton, B.L. Bodirsky, J. Bogard, et al. 2020. "Innovation Can Accelerate the Transition Towards a Sustainable Food System." Nature Food 1: 266–272.
29. Herrero M., P.K. Thornton, C. Mason-D'Croz, J. Palmer, B.L. Bodirsky, P. Pradhan, C.B. Barrett, et al. 2021. "Articulating the Impact of Food Systems Innovation on the Sustainable Development Goals." Lancet Planetary Health 5(1): E50–E62.
30. Hickson K, and P. Thornton. 2020. Updates to the Number of Agricultural Holdings by Country Dataset of Lowder et al. (2016). Unpublished, CIAT and ILRI.
31. Hu, C., X. Zhang, T. Reardon, and R. A. Hernandez. 2019. "Value-Chain Clusters and Aquaculture Innovation in Bangladesh." Food Policy 83 (February): 310–326.
32. Huang, H., X. Gong, and B. Huang. 2010. "The Competitive Advantages of Agricultural Industrial Clusters Based on Specialization: A Case Study of Shouguang County Vegetable Industry Cluster." Agricultural Economic Issues 4: 64–111 (in Chinese).
33. Kahan, D., R. Bymolt, and F. Zaal. 2018. "Thinking Outside the Plot: Insights on Small-Scale Mechanization from Case Studies in East Africa." Journal of Development Studies 54(11): 1939–1954.
34. Laborde Debucquet, D., S. Murphy, M. Parent, J. Porciello, and C. Smaller. 2020. Ending Hunger, Increasing Incomes, and Protecting the Climate: What Would It Cost Donors? Winnipeg, Canada: International Institute for Sustainable Development (IISD).
35. Li, S., C. Zhu, X. Ma, and H. Li. 2015. "Centralized Seedlings and Machine-Transplanted Rice in Nantong City in China." China Rice 213: 72–74 (in Chinese).
36. Liverpool-Tasie, L.S.O., B. Omonona, A. Sanou, W. Ogunleye, S. Padilla, and T. Reardon. 2017. "Growth and Transformation of Chicken and Eggs Value Chains in Nigeria." Nigerian Journal of Agricultural Economics 7(1): 1–15.
37. Liverpool-Tasie, L.S.O., T. Reardon, and B. Belton. 2020. "'Essential Non-Essentials': COVID-19 Policy Missteps in Nigeria Rooted in Persistent Myths about African Food Value Chains." Applied Economic Perspectives and Policy 43(1): 205–224.
38. Lowder, S.K., J. Skoet, and T. Raney. 2016. "The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide." World Development 87 (November): 16–29.
39. Masiwa, D. 2020. "Fed-Up Farmers to Turn to Facebook to Sell Their Produce." Food for Mzansi, May 13.
40. McCord, P.F., M. Cox, M. Schmitt-Harshe, and T. Evans. 2015. "Crop Diversification as a Smallholder Livelihood Strategy within Semi-Arid Agricultural Systems Near Mount Kenya." Land Use Policy 42 (January): 738–750.
41. Milder, J.C., S.J. Scherr, and C. Bracer. 2010. "Trends and Future Potential of Payment for Ecosystem Services to Alleviate Rural Poverty in Developing Countries." Ecology and Society 15(2): 4.
42. Minten, B., T. Reardon, K.M. Singh, and R. Sutradhar. 2014. "The New and Changing Roles of Cold Storages in the Potato Supply Chain in Bihar." Economic and Political Weekly 49(52): 98–108.
43. Minten, B., S. Tamru, E. Engida, and T. Kuma. 2016. "Feeding Africa's Cities: The Case of the Supply Chain of Teff to Addis Ababa." Economic Development and Cultural Change 64(2): 265–297.
44. Minten, B., B. Mohammed, and S. Tamru. 2020. "Emerging Medium-Scale Tenant Farming, Gig Economies, and the COVID-19 Disruption: The Case of Commercial Vegetable Clusters in Ethiopia." The European Journal of Development Research 32 (October): 1402–1429.
45. Moser, C.M., and C.B. Barrett. 2006. "The Complex Dynamics of Smallholder Technology Adoption:

The Case of SRI in Madagascar." Agricultural Economics 35(3): 373–388.
46. Ouin, A., and F. Burel. 2002. "Influence of Herbaceous Elements on Butterfly Diversity in Hedgerow Agricultural Landscapes." Agriculture, Ecosystems & Environment 93(1-3): 45–53.
47. Paudel, G.P., D.B. Kc, D.B. Rahut, S.E. Justice, and A.J. McDonald. 2019. "Scale-Appropriate Mechanization Impacts on Productivity among Smallholders: Evidence from Rice Systems in the Mid-Hills of Nepal." Land Use Policy 85 (June): 104–113.
48. Qanti, S.R., T. Reardon, and A. Iswariyadi. 2017. "Triangle of Linkages among Modernizing Markets, Sprayer Traders, and Mango-Farming Intensification in Indonesia." Bulletin of Indonesian Economic Studies 53(2): 187–208.
49. Reardon, T. 2015. "The Hidden Middle: The Quiet Revolution in the Midstream of Agrifood Value Chains in Developing Countries." Oxford Review of Economic Policy 31(1): 45–63.
50. Reardon, T., R. Echeverría, J. Berdegué, B. Minten, S. Liverpool-Tasie, D. Tschirley, and D. Zilberman. 2019. "Rapid Transformation of Food Systems in Developing Regions: Highlighting the Role of Agricultural Research & Innovations." Agricultural Systems 172 (June): 47-59.
51. Reardon, T., and J. Swinnen. (2020). "COVID-19 and Resilience Innovations in Food Supply Chains." In COVID-19 & Global Food Security, eds. J. Swinnen and J. McDermott, 132–136. Washington, DC: International Food Policy Research Institute.
52. Reardon, T., B. Belton, L.S.O. Liverpool-Tasie, L. Lu, C.S.R. Nuthalapati, O. Tasie, and D. Zilberman. 2021. "E-Commerce's Fast-Tracking Diffusion and Adaptation in Developing Countries." Applied Economic Perspectives and Policy. https://doi.org/10.1002/aepp.13160
53. Reardon, T., A. Heiman, L. Lu, C.S.R. Nuthalapati, R. Vos, and D. Zilberman. 2021. "'Pivoting' by Food Industry Firms to Cope with COVID-19 in Developing Regions: E-Commerce and 'Co-Pivoting' Delivery-Intermediaries." Agricultural Economics (preprint). https://doi.org/10.1111/agec.12631
54. Ricciardi, V., N. Ramankutty, Z. Mehrabi, L. Jarvis, and B. Chookolingo. 2018. "How Much of the World's Food Do Smallholders Produce?" Global Food Security. 17 (May): 64–72.
55. Ricciardi, V., Z. Mehrabi, H. Wittman, D. James, and N. Ramankutty. 2021. "Higher Yields and More Biodiversity on Smaller Farms." Natural Sustainability. https://doi.org/10.1038/s41893-021-00699-2
56. Ritchie, H., and M. Roser. 2017. "CO_2 and Greenhouse Gas Emissions." Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions
57. Ruysschaert, D., and D. Salles. 2014. "Towards Global Voluntary Standards: Questioning the Effectiveness in Attaining Conservation Goals: The Case of the Roundtable on Sustainable Palm Oil (RSPO)." Ecological Economics. 107(November): 438–446.
58. Samberg, L.H., J.S. Gerber, N. Ramankutty, M. Herrero, and P.C. West. 2016. "Subnational Distribution of Average Farm Size and Smallholder Contributions to Global Food Production." Environmental Research Letters 11(November): 124010.
59. Stifel, D., B. Minten, and B. Koru. 2016. "Economic Benefits of Rural Feeder Roads: Evidence from Ethiopia." Journal of Development Studies. 52(9): 1335–1356.
60. Swinnen, J., and R. Kuijpers. 2019. "Value Chain Innovations for Technology Transfer in Developing and Emerging Economies: Conceptual Issues, Typology, and Policy Implications." Food Policy 83(February): 298–309.
61. Takeshima, H. 2018. "Mechanize or Exit Farming? Multiple-Treatment-Effects Model and External Validity of Adoption Impacts of Mechanization among Nepalese Smallholders." Review of Development Economics 22(4): 1620–1641.
62. Thurlow, J., P. Dorosh, and B. Davies. 2019. "Demographic Change, Agriculture and Rural Poverty." In Sustainable Food and Agriculture: An Integrated Approach, eds. C. Campanhola and S. Pandey, 31 – 53. London: Elsevier and FAO.
63. Van Campenhout, B., D.J. Spielman, and E. Lecoutere. 2021. "Information and Communication Technologies to Provide Agricultural Advice to Smallholder Farmers: Experimental Evidence from Uganda." American Journal of Agricultural Economics 103(1): 317–337.
64. Vandercasteelen, J., S.T. Beyene, B. Minten, and J. Swinnen. 2018. "Big Cities, Small Towns, and Poor Farmers: Evidence from Ethiopia." World Development 106(June): 393–406.
65. Vardhan, V. 2020. "Impact of the COVID-19 Pandemic on Retailing in Emerging Countries." [PowerPoint]. Euromonitor International. Unpublished.
66. Wang, X., F. Yamauchi, and J. Huang. 2016. "Rising Wages, Mechanization, and the Substitution Between Capital and Labor: Evidence from Small Scale Farm System in China." Agricultural Economics 47(3): 309–317.
67. Wells, G., J.A. Fisher, I. Porras, S. Staddon, and C. Ryan. 2017. "Rethinking Monitoring in Smallholder Carbon Payments for Ecosystem Service Schemes: Devolve Monitoring, Understand Accuracy and Identify Co-Benefits." Ecological Economics 139(September): 115–127.
68. Woodhill, J., S. Hasnain, and A. Griffith. 2020. Farmers and Food Systems: What Future for Small-

Scale Agriculture? Oxford: Environmental Change Institute, University of Oxford.
69. World Bank. 2003. Reaching the Rural Poor: A Renewed Strategy for Rural Development. Washington, DC.
70. World Bank. 2016. Poverty and Shared Prosperity 2016: Taking on Inequality. Washington, DC.
71. Wouterse, F., S. Murphy, and J. Porciello. 2020. “Social Protection to Combat Hunger.” Nature Food 1(9): 517–518.
72. Yagura, K. 2020. “Rapid Diffusion of Combine Harvesters in Cambodian Rice Farming: A Business Analysis.” Asian Journal of Agriculture and Development 17(1) 71–88.
73. ZEF (Center for Development Research) and FAO (Food and Agriculture Organization of the United Nations). 2020. Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG2). Rome and Bonn.
74. Zhang, X., J. Yang, and T. Reardon. 2017. “Mechanization Outsourcing Clusters and Division of Labor in Chinese Agriculture.” China Economic Review 43(April): 184–195.

UNITED NATIONS
FOOD SYSTEMS
SUMMIT 2021
The Scientific Group for the
UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

BUILDING RESILIENCE TO VULNERABILITIES, SHOCKS AND STRESSES – ACTION TRACK 5 –

by Thomas W. Hertel, Ismahane Elouafi, Frank Ewert and Morakot Tanticharoen

ABSTRACT

Transforming food systems involves five action tracks: i) access to safe and nutritious food, ii) sustainable consumption, iii) nature-positive production, iv) equitable livelihood, and v) resilience to shocks and stress.

Action Track 5 of the Food Systems Summit aims to ensure food system resilience in the face of increasing stresses from climate change, population growth and conflict over limited natural resources. We identify five distinct capacities that are key to a resilient food system in the face of these shocks: (i) to anticipate, (ii) to prevent, (iii) to absorb, (iv) to adapt to an evolving risk and (v) to transform in cases where the current food system is no longer sustainable. Resilience at the individual, community, government and global food system level must be built in such a way that the economic, so-

ABOUT THE AUTHORS

Thomas W. Hertel (USA), Professor of Agricultural Economics at Purdue University and Executive Director of the Global Trade Analysis Project (GTAP).

Ismahane Elouafi (Morocco / Canada), Chief Scientist of the Food and Agriculture Organization (FAO) of the United Nations.

Frank A. Ewert (Germany), Scientific Director, Leibniz Centre for Agricultural Landscape Research (ZALF).

Morakot Tanticharoen (Thailand), Professor and Senior Advisor to the President of the National Science and Technology Development Agency (NSTDA), research in microbiology and biotechnology.

cial and environmental bases to generate food security and nutrition for current and future generations are not compromised anywhere in the world. This means that it is equitable in a financial sense (economic resilience), it is supportive of the entire community (social resilience), and it minimises harmful impacts on the natural environment (ecological resilience).

There are a number of key trade-offs which must be navigated as we strive to achieve greater food system resilience. These include the need to deliver short-term humanitarian aid without jeopardising long run development, mitigation of rising global temperatures even as the food system adapts to the inevitable changes in the earth's climate, taking advantage of the benefits of globalisation while avoiding the downsides, and encouraging agricultural production and boosting rural incomes while also protecting the environment. All of these trade-offs become more pronounced in the context of small farms operating in marginal environments. In order to address these trade-offs, co-operation and coordination across policy makers, local communities and public and private institutions and investors will be required.

A range of local, regional, national and global solutions covering different parts and contexts of the food system have been reviewed to understand progress and challenges in building resilience to improve food security. The resilience framework is helpful to conceptualise complex problems related to food security and allows us to point to important challenges that need to be overcome. From this analysis we conclude that developing an operational resilience approach is always context-specific and requires the involvement of relevant local, national and international actors, organisations and agencies. Hence, there is no single game-changing solution that will ensure resilience across multiple food security challenges. Instead, adopting resilience as a systems approach to support the conceptualisation and operationalisation considering the respective actors will contribute to the development of context-specific solutions. Beyond that, much will be gained by highlighting successful solutions and facilitating exchange of tools, data, information and knowledge and capacity. This will also contribute to the further develop of the resilience approach as a key concept to achieve food security.

INTRODUCTION

Action Track 5 seeks to provide an integrative perspective across all other action tracks encompassing the entire food system but with the specific focus on building resilience (Fig. 1). This review of the state of scientific understanding of resilience is broken into four parts: (Fig. 1), (i) the challenges faced by the food system and our ambition to meet these challenges, (ii) the identification of key trade-offs and synergies, (iii) operational aspects towards practical solutions and, as part of this, (iv) the contextualisation of specific food system related problems.

Following the (OECD 2020) and the FAO UN (FAO 2020), we distinguish five capacities of resilient food systems

Figure 1 Representation of the integrative perspective of Action Track 5 across other action tracks and key elements addressed by Action Track 5 to build food system resilience.

Figure 2 Schematic representation of the scope of food system resilience as proposed by Action Track 5 considering five capacities of food systems to anticipate, to prevent impacts of changes and shocks, to absorb, to adapt and to transform, and activities to develop concrete targeted solutions considering the respective food system context and to develop required operational measures and tools.

to deal with changes or shocks (Fig. 2), i.e. (i) to anticipate, (ii) to prevent, (iii) to absorb, (iv) to adapt to an evolving risk and (v) to transform in cases where the current food system no longer sustainable. Our definition also includes two more aspects to achieve targeted solutions. On the one hand, building resilience requires clear understanding and consideration of the specific food system context (region, time-period, system complexity, involved actors, institutional structures, etc.). On the other hand, conceptual ideas need to be operationalised, developing concrete measures and processes for the five capacities of resilient food systems.

CHALLENGES AND AMBITIONS

As highlighted in the Global Assessment Report on Disaster Risk Reduction (UN Office for Disaster Risk Reduction 2019), global change and the increasingly interconnected nature of society are inducing unprecedented hazards that are likely to prove disastrous for many of the world's most vulnerable populations. This has led the United Nations to issue a report focusing specifically on resilience guidance (United Nations 2020). Action Track 5 of the Food Systems Summit aims to ensure such resilience in the regional to national and global food system(s), such that people are empowered to prepare for, withstand, and recover from instability. They must be able to participate in a food system that, despite shocks and stressors, delivers food security, nutrition and equitable livelihoods for all. Resilience at the individual, community, government and global food system level must be built in such a way that the economic, social and environmental bases to generate food security and nutrition for current and future generations are not compromised anywhere in the world. This means that it is equitable in a financial sense (economic resilience), it is supportive of the entire community (social resilience), and it minimises harmful impacts on the natural environment (ecological resilience).

The concept of resilience first emerged in the context of ecological stability theory (Holling 1973). It was directed at understanding the capacity of ecosystems to sustain perturbations persisting in the original state. The resilience concept has evolved to address complex socio-ecological systems and their capacity to adapt while remaining within critical thresholds (Folke 2016). In the context of food systems, resilience has contributed to the foundation of adaptive resource management (Walters 1986) with widespread use in cropping and farming systems (Webber et al. 2014). This concept has also surfaced in the field of economics where it has been linked to 'development resilience' which focuses on the capacity to avoid and escape from poverty in the face of unforeseen external shocks and stressors (Barrett and Constas 2014). This literature explicitly considers issues of risk, dynamics, and ecological feedback. The recent OECD report (2020) on agricultural resilience usefully distinguishes between: (a) risks that are best managed at the farm level, i.e. normal business risks, (b) larger, less frequent risks requiring market interventions such as insurance and futures markets, and (c) infrequent, catastrophic risks requiring emergency assistance.

Box 1: Food System Resilience during the COVID-19 Pandemic

Evidence about the impact of COVID-19 on food system resilience is just beginning to emerge in the peer-reviewed literature (High Level Panel of Experts 2020), but it is evident that the pandemic is affecting all four pillars of food security (Laborde et al. 2020). Estimates of the increase in food insecurity range from 83-132 million, reflecting and exacerbating many of the existing inequities in the food system (Klassen and Murphy 2020; FAO 2020b). These impacts are not just being felt in the developing world. In the United States, food insufficiency increased three-fold compared to 2019. Food insufficiency among black adults is estimated to be two to three times higher than for whites and reached one in five individuals in July of 2020 (Ziliak (2020)).

Food insufficiency captures lack of access to food due to limited resources. This can arise in a pandemic due to limited availability, high prices or loss of income. Evidence to date shows that the impact of the pandemic on prices and food availability varies widely across commodities and countries. In India, where there was a sudden, unanticipated lockdown put in place for three weeks in late March/early April, the evidence on price impacts is mixed. In a detailed study based on data from just one of the largest online retailers in India, Mahajan and Tomar (2020) find that online prices during the lockdown were largely unaffected. Instead, the availability of food was reduced, by 8% in the case of fruits and vegetables and 14% for edible oils. In contrast to these findings, Narayanan and Saha (2020) use publicly available data from the Government of India to analyse urban food prices across a range of markets and suppliers and find evidence of marked price increases during the lockdown – particularly for pulses, oils and vegetables – ranging from 3.5% to 28% depending on the commodity in question. Nonetheless, a recent household survey in Ethiopia suggests that the food system has proven relatively robust in that country, with dietary intake being largely unaffected by the pandemic (Hirvonen, Brauw, and Abate 2021).

The consequences of the COVID-19 pandemic for labour markets, and hence crop cultivation activities (Ayanlade and Radeny 2020) as well as household incomes, appears to a key channel for increasing food insecurity (Béné 2020). In West Africa, the agricultural workforce already has a poor nutritional and health profile and are especially vulnerable to pandemic illness during critical planting and harvesting periods (Ali et al. 2020). In a forthcoming model-based study of the impacts of COVID-19, Laborde, Martin and Vos (2020) predict that the global recession caused by this pandemic will be much deeper than that of the 2008-2009 financial crisis. The predicted increases in poverty are concentrated in South Asia and Sub-Saharan Africa with more severe impacts in urban areas than in rural communities. They project that almost 150 million people will fall into extreme poverty and food insecurity as a result of this pandemic. When combined with limited health care resources, large households and high incidence of co-morbidities the human toll is expected to be extreme in sub-Saharan Africa (Walker et al. 2020).

Food systems are becoming increasingly global, dynamic, and complex. Today, food goes through agri-food supply chains involving networks of farms, production or processing facilities, and storage and distribution channels. With this growing complexity, new and challenging risks are emerging as evidenced by the ongoing COVID-19 pandemic the impacts of which are skewed towards the world's most vulnerable populations (Box 1). In addition, there are many other, ongoing challenges, including technological accidents, infectious diseases, transportation hazards, cyber-attacks, product contamination, theft, and unexpected shutdowns of key supply chain nodes (Leat and Revoredo-Giha 2013; Manning and Soon 2016). Such disruptions could lead to significant public health and economic consequences. A study by the World Bank finds that the impact of unsafe food costs low- and middle-income economies about US$ 110 billion in lost productivity and medical expenses each year (Jaffee et al. 2019). Nonetheless, a large proportion of these costs could be avoided by adopting preventative measures that improve how food is handled along the global supply chains pointing to the great scope for collaboration and learning using South-South and Triangular cooperation adopted by several UN Organizations, namely FAO, IFAD, and WHO.

Successful management of socio-ecological systems necessitates understanding the contextual factors that drive changes in resource-use patterns and influence societal capacity to adapt in the face of stresses. Schwarz et al., (2011) find that perceptions of risk, preference, belief, knowledge, and experience are key factors determining whether and how adaptation takes place, at both the individual and societal levels. They suggest that elements of good community-level governance such as social cohesion, leadership, or individual support for collective action improve the perception that people have of the resilience of their community. Creation of a food system that delivers broad-based benefits for all people, requires covering all of the societal bases of equity and inclusiveness. Developing capacity to improve resilience requires actions at both the individual and societal levels. Capacity building for resilient food systems is a non-static process to develop stronger capacity that enables food systems to be more resilient to future shocks (Babu and Blom 2014).

What are the key trade-offs and synergies?

Over the next decade, food systems will face a complex challenge to deliver sufficient safe and nutritious food for all in a sustainable manner in the face of a changing climate, while reducing greenhouse gas emissions and preserving ecosystems and biodiversity, and providing equitable livelihoods to all of the actors in the food chain and promoting sustainable development. Attainment of these diverse goals while ensuring food system resilience gives rise to complex synergies and trade-offs across economic, political, social and environmental dimensions that need to be considered in setting priorities across productivity growth, environmental sustainability and hunger reduction (Béné et al., (2019)). In this section of the paper, we review some of the most salient trade-offs and synergies that arise in the context of food system resilience.

Short-term humanitarian aid vs. long-term development assistance:

Based on our definition of resilience (Fig. 2), an important component involves anticipating and preventing adverse impacts of external shocks to the food system. However, less than one percent of emergency assistance goes to disaster prevention and preparedness (Kellet and Sparks 2012). The UN Secretary General convened a World Humanitarian Summit in 2016 to deal with these issues. The summary report calls for a long-sought commitment to change the way humanitarian and development actors work together (UN Secretary General 2016). Particular emphasis is placed on health and education of children and young people in crisis. In some cases such joined-up activities are complementary. However, linking actions and interventions that involve inherent trade-offs such as disaster risk reduction and conflict prevention remains a significant challenge (Peters, Keen, and Mitchell 2013).

Rural and urban communities:

To identify potential trade-offs and synergies between rural and urban communities, Blay-Palmer et al., (2018) assess the value and utility of the evolving City Region Food Systems approach to improve our insights into flows of resources from rural to peri-urban to urban areas. Resolution of conflicts at the boundaries of agricultural and other land uses and communities, e.g. forest, urban, diversification and specialisation, as well as the need to combine the benefits of diversification with scale economies. Conflict frequently arises at the boundary of agriculture and forests where encroachment on natural habitat can lead to conflict, for example between wildlife and rural populations (Shaffer et al. 2019). Rural and urban communities also face competition for resources, including land and water. Agriculture accounts for nearly three-quarters of water consumption globally. As urban and suburban water scarcity emerges, we expect some reallocation of this resource to occur (Molden et al. 2007). In contrast, rural-urban labour movement can offer an important source of resilience. Migration is perhaps the most important resource flow. This is generally motivated by a desire to diversity and raise household income. A survey of 1,874 rice-farming households in Northeast Thailand found that income from migration represented 38% of their incomes (Paris et al. 2009). In addition, better knowledge and skills through migration and education at their destination have contributed to improvements in agriculture, e.g. improvement of land use techniques taken place in the Northeast region (Huguet and Aphichat Chamratrithirong 2011). Migration can also provide an important adaptation strategy to climate related risks (Sterly 2020).

Climate change adaptation and mitigation:

Much progress has been achieved in identifying possible trade-offs between measures to support climate adaptation and mitigation in agriculture. Most prominent is the climate-smart agriculture approach (CSA), defined by the FAO as “agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes GHGs (mitigation) where possible, and enhances achievement of national food security and development goals” (Reiche et al. 2012; Lipper et al. 2014). However, recent analyses suggest that knowledge about the exploitation of interrelationships between adaptation and mitigation measures in agriculture remains limited and greatly depend on their context, design and implementation, so that actions have to be tailored to the specific conditions (Kongsager 2018). Even less is known for the larger food system but the importance to identify tailored, resilient solutions considering the context of specific conditions will also apply.

Globalisation vs. self-sufficiency:

There are important trade-offs between integration into global supply chains and world markets, on the one hand, and the desire for locally sourced products, with shortened supply chains and greater food self-sufficiency, on the other. Better integration into world markets can ensure food security in the face of local drought, flooding and other natural disasters. In pre-colonial India, weather-induced famines were common, resulting in tens of millions of deaths when flooding or drought destroyed local crops. However, with the introduction of railroads in colonial India, Burgess and Donaldson (2010) find a dramatic reduction in the number of deaths associated with comparable extreme weather events, suggesting that improved market integration greatly enhanced food security by allowing for timely food imports. Recent studies of the role of international trade in mitigating adverse impacts of climate change reinforce the benefits of globalisation for resilience to adverse climate impacts (Baldos and Hertel 2015; Gouel and Laborde 2018). However, when the source of adverse shocks is the global market, countries may have an incentive to insulate themselves from these developments. The problem with this strategy is that, the more countries insulate themselves from world markets, the more volatile those markets will become, as was found in the context of the food price crises of 2006-2008 and 2010-2011 (Martin and Anderson 2012). This harms those countries – often the poorest – who rely on these markets for critical food imports.

Livestock production as a source of income and nutrition vs. environmental sustainability:

The role of livestock in a resilient food system has been recently challenged on the argument that reduced consumption of livestock products will enhance health outcomes while reducing environmental stress (Willett et al. 2019). Beef production, in particular, has been shown to be extremely resource intensive, resulting in significant environmental stress (Eshel et al. 2014). However, in many developing countries, livestock products are a critical source of dietary diversity, particularly in the critical first 1,000 days of life (Alonso, Dominguez-Salas, and Grace 2019). Livestock production is also crucial for resilience as this contributes in several ways to daily subsistence of rural poor in developing countries through food production, income generation, labour and transportation, as mobile assets and wealth storage, integration with agricultural systems, diversification of activities, utilisation of marginal lands and women's empowerment (FAO 2016).

All of these trade-offs are made more challenging in the context of small farms, operating in marginal environments:

Small farmers play a crucial role in fostering rural growth by playing multifunctional roles in development. A large body of empirical research argues that smallholders are still key to global food security and nutrition. Although these farms account for only 12% of the world's farmland, they provide livelihoods for more than 2 billion people and produce about 80% of the food in sub-Saharan Africa and Asia (Paloma, Riesgo, and Louhichi 2020). Empirical evidence suggests that populations living on less favoured agricultural lands in developing countries cope with major poverty-environment traps (Barbier 2010; Barbier and Hochard 2019). These traps arise in the context of severe biophysical constraints and limited market access that limit profitability of production and restrict off-farm employment opportunities (Barbier and Hochard, 2018). The poor are often trapped in a vicious downward spiral as they overuse environmental resources to survive from day to day, and the impoverishment of their environmental resources further deprives them, making their survival ever more uncertain and difficult (Gray and Moseley 2005). Since marginality is not a permanent state (Gurung and Kollmair 2005) and those affected by it can be helped with targeted support and appropriate policies in place, there is an opportunity to target the oft-overlooked rural poor under marginal conditions. These marginalised communities will benefit from risk-informed and safety net social protection schemes as well as remuneration for ecosystem services they can provide through wise management and custodianship of renewable natural resources

In order to address trade-offs properly, attention is required by:

- Policy makers, to strengthen coordination among international actors and across scales, allowing for positive synergies in which governments and NGOs can learn from the successes and failures of other nations and institutions (Wiener and Alemanno 2015).
- Institutions, to combine activities at "multilateral", "bilateral" institutions, NGOs and foundations, as well as creating suitable consultative and participatory platforms so the voices of smallholders and food workers can be heard by policy makers.
- Coordinated public and private investments in the food sector focusing on the co-creation of solutions that meet individual and collective ambitions for tackling human and planetary crisis. (Mushtaq et al., (2020)).
- Local communities to mobilise for collective action in the face of increasing hazards (UN Office for Disaster Risk Reduction 2019).

What needs to be done?

To address these resilience challenges, solutions need to be defined around cross cutting levers of joined-up policy reform, coordinated investment, accessible financing, innovation, traditional knowledge, governance, data and evidence, and empowerment. Much can be learned from successful ongoing initiatives and programmes. Hence, a range of concrete solutions are reviewed in this section to highlight how food security challenges have been addressed successfully but also to identify limitations of present approaches. The examples are summarised in table 1 describing the main contributions for building resilience, the organisations and agencies involved, and the challenges and synergies addressed.

Early warning system:
An important step to improve resilience is strengthening the capacity to monitor and analyse vulnerability, capacities and risks (World Food Programme 2020). There are now nearly two dozen organisations involved in food security and drought early warning systems, a number that has been growing since the inception of FEWS NET in the mid-1980s (Funk et al. 2019). The joint FAO-World Food Program Early Warning System now provides up to date analysis of acute food security hotspots and plays a key role at the global level (FAO and WFP 2020). Strengthening resilience has emerged as an important means to prevent, mitigate and prepare for risks associated with a range of threats to development. Resilience is also a key element of the UN pillars of development – human rights, peace and security – and resilience is a key to achieving sustainable development (UNISDR 2015). At the regional level, a promising example of actions to promote resilience is offered by the "Cadre Harmonise du Sahel" which provides a set of functions and protocols for the identification and analysis of populations in the Sahel region at risk of food and nutrition insecurity. It seeks to answer questions related to the severity of a given crisis, how many people are affected, when and where intervention should be undertaken, and what are the limiting factors? Stakeholders include national, regional (West Africa-wide) and international entities.

Table 1 Application of the resilience approach to develop solutions for food security considering contributions (capacities) for building resilience, the organisations and agencies involved and the trade-offs and synergies addressed and achieved, respectively.

Solution	Contribution to resilience	Institutional Engagement (examples)	Trade-Offs and Synergies
Early warning systems	Anticipate, Prevent, Adapt	FAO, WFP, FEWS NET, Cadre Harmonise du Sahel	Humanitarian relief vs. development assistance; regional coordination and collective actions (adaptation)
Weather index insurance	Absorb, Adapt	R4, WBCIS, WFP, IFAD	Enhanced through improved data and monitoring; reduces credit risk
Enhanced market information	Anticipate, Prevent, Absorb, Adapt	Agricultural Market Information System	Prevents overreaction to shocks; allows for informed decision-making
Food insecurity in conflict zones	Anticipate, Prevent, Absorb, Adapt	FAO, WFP, national agencies	Joining resources, implementing complementary activities for effective resource utilisation and supporting communities
Enhanced rural-urban labour mobility	Absorb, Adapt, Transform		Facilitates climate resilience; enhanced through education
Transport infrastructure	Absorb, Transform	Railroads in colonial India	Improved market access benefits rural communities
Irrigation systems	Prevent, Absorb, Adapt	IWMI, FAO	Enhanced climate resilience; increased farmers' income; potential for groundwater depletion
Social protection	Anticipate, Absorb, Transform	Ethiopia: Productivity Safety Net; FAO: Cash+ programme	Avoid poverty traps; improved health and nutrition; asset and skill enhancement
Aquaculture diversification	Absorb, Adapt, Transform	Integrated Agriculture-Aquaculture programme	Income gains; Enhanced dietary outcomes; lose gains from specialisation; improved nutrition, water re-use/circulation
Crop diversification	Absorb, Adapt, Transform	ICBA, CFF, CGIAR,	improved food security,
Post-harvest loss reduction	Anticipate, Absorb, Transform	Gates Foundation: PIC	Improve food security; encourage adoption of new seed varieties
Development, dissemination and utilisation of agricultural big data	Anticipate, Adapt, Transform	WASCAL; CGIAR: INSPIRE; AgMIP	Enhances weather insurance, market, information and research impacts
Enhanced equity in food systems	Absorb, Adapt, Transform	FAO, IFAD	Improved development outcomes; Enhanced indigenous capacity
Agro-ecology	Anticipate, Prevent, Absorb	ICBA	improved ecosystems vs. reduced farmer incomes
Transnational policy coordination	Anticipate, Pervent, Adapt	Sahel-CILSS; EU-JPI; PPPs	Improve human health
Food safety policies	Ancitipate, Prevent, Adapt	FDA: PCHF in Thailand; Bangladesh Food Safety Network	Improved health outcomes
Community organisation	Anticipate, Adapt, Transform	Bann Samkha community action	Circular economy; enhanced incomes

Weather index insurance:

As climate extremes become more frequent and more pronounced in the future, producers will face increasing risks. Weather variability will affect agricultural seasons through changes in rainfall and temperature patterns that affect both production quantity and quality. Effective drought risk management requires an early warning system (e.g. FEWS NET), risk assessment, drought preparedness, mitigation and response (Funk and Shukla, 2020). Traditional risk-sharing mechanisms within a community have been a key vehicle for protecting against idiosyncratic shocks to income. However, these do not perform well when adverse events such as drought affect an entire community (covariate risks). Weather index insurance has been developed specifically for such circumstances (Gine, Townsend, and Vickery 2008). Here, households enrol at the beginning of the season and payouts are made based on (e.g.) rainfall in the region (not the outcome on their specific farm) dropping below a trigger level. It is typically provided initially by the public sector, and can entail relatively low overhead if the triggers are transparent and not subject to manipulation.

Since its inception, weather index insurance has faced challenges in reaching the poorest households tend who typically face they face severe credit constraints (Binswanger-Mkhize 2012). However, recent innovations are permitting index insurance to thrive in a number of key locations (Hazell et al. 2010). In India, participation in the Weather Based Crop Insurance System (WBCIS) expanded from 300,000 in 2009 to more than 13 million in 2013. Case studies of these successes suggest that participation in index insurance enhances farmers' access to credit, allowing smallholders to participate in more risky, higher return farming activities (CCAFS 2015). The R4 initiative in Ethiopia and Senegal has a clear plan for introducing weather index insurance in new locales, operating in partnership with private financial institutions and insurers. They begin with a dry run in which local farmers and experts are consulted and the plan is modified to fit the local conditions. It is subsequently rolled out to several thousand farmers and further refined prior to being scaled up. Insured farmers have boosted savings, increased the number of oxen and increased access to loans. The R4 initiative has been particularly successful at reaching low-income farmers. However, this programme continues to face data challenges in due to relatively sparse ground-based weather monitoring stations in many parts of sub-Saharan Africa (CCAFS 2015).

Enhanced market information:

The recent pandemic has heighted some important global food system resilience successes. OECD trade ministers held a record number of meetings during 2020 (all virtual), and these meetings were substantive, focusing on specific measures to facilitate the movement of critical goods and services during the pandemic. This was reflected in the fact that, by OECD measures, growth in trade facilitation activities outweighed trade restrictions during the COVID-19 pandemic (Jansen 2020). Increased digitalisation of trade regulations and monitoring has facilitated more rapid movement of critical goods. Meanwhile, where export restrictions have been put in place, they have been targeted, transparent and temporary. This has been reflected in the fact that, unlike the commodity crisis period: 2006-2011, when agricultural prices became extremely volatile in the wake of widespread cascading export restrictions, commodity prices were relatively flat throughout 2020 (Jansen 2020). The OECD attributes much of this stability to the implementation of the Agricultural Market Information System (AMIS). AMIS provides up to date information on agricultural commodity prices and availability, thereby preventing over-reactions on the part of governments and markets (Jansen 2020). This has resulted in much more resilient global markets for agricultural products.

Addressing food insecurity in conflict zones:

Over the past two decades, conflict-plagued countries' share of stunted children grew from 46% to 75% (FAO 2017). There is mounting evidence that climate change is a key driver of conflict (Hsiang, Burke, and Miguel 2013; Maystadt, Calderone, and You 2015), suggesting that this trend will only increase, absent significant interventions. Strengthening dispute resolution mechanisms and sound natural resource management might significantly help to reduce conflict in fragile states (Calderone, Headey, and Maystadt 2014). The World Food Program has introduced several programmes to address food insecurity in conflict zones, such as the Food Assistance for Assets programme, which aims to address the most food-insecure people's immediate food needs with cash, vouchers, or food transfers while helping to improve their long-term food security and resilience. Within this programme, people receive cash or food-based transfers while they boost assets, such as constructing a road or rehabilitating degraded land to improve their livelihoods. The combination of conditional food assistance and asset creation work helps food-insecure communities to shift away from reliance on humanitarian aid to achieve more sustainable food security.

The crisis in Somalia offers an example of the compound risks from severe weather events coinciding with conflict. Rapid shifts from drought to flooding in the context of ongoing violence and conflict have led to a series of food security crises in that country. The World Food Program (WFP) and the Food and Agriculture Organization (FAO), in conjunction with international/local NGOs have joined forces to implement a multi-year, joint resilience programme in Burao and Odweine districts of Somaliland. The programme allows agencies to pull resources together and implement complementary activities, contributing to effective resource utilisation and supporting communities over long periods. Through this partnership, water catchments, vegetable gardens, and nutrition-awareness programmes were implemented.

Social protection:
In Ethiopia, an effort is underway aimed at breaking the cycle of dependence on food aid. The Productivity Safety Net Program (PSNP) focuses on the chronically food-insecure households, providing cash or food transfers on a predictable basis for five years, along with financial and technical support. Where there are able-bodied beneficiaries, they are required to provide labour in exchange for these transfer payments. The goal is to help these households build assets which can sustain them through future crises, along with contributing to the construction of rural infrastructure.

Integrating smallholders more fully into regional markets can also enhance resilience. In Ethiopia, a pilot effort dubbed P4P: Purchase for Progress, run by the WFP, works through farmer organisations to better integrate farmers into these markets. This involves improving the efficiency of these organisations, reducing transactions costs and improving information flows and as well as encouraging additional value-added for smallholder-grown products. In some cases, P4P also involves the purchase of commodities for use in the WFP's food aid activities. A recent study (Gelo et al. 2020) of the P4P pilot project in Ethiopia finds that these interventions have resulted in significant increases in household welfare – as measured by a roughly 25% increase in spending – as well as sharply increased investment in children's education. This suggests that such programmes can address both short-term resilience as well as longer-term development objectives.

Aquaculture diversification:
Aquaculture can also provide an important vehicle for improving the resilience and well-being of smallholder farm households, particularly in Asia and Sub-Saharan Africa. In Malawi, Integrated Agriculture-Aquaculture (IAA) farming practices have been introduced to help farmers boost earnings and increase food security. Integrated farming enables farmers to boost total farm productivity by 10% while increasing farm income by 61% more income (Dey et al. 2007), as well as boosting household resilience during times of drought, leading one farmer to note: "Fish in the pond is like money in the bank." (https://www.worldfishcenter.org/content/combining-aquaculture-and-agriculture-promote-food-security-malawi). This has also resulted in a tripling of fresh fish consumption, thereby enhancing the protein content of diets. The techniques used by the IAA programme are simple and low-cost. Fish are fed maize bran and household leftover while manure from goats, chickens and rabbits help to fertilise the ponds (Dey et al. 2007).

Post-harvest loss reduction:
Programmes aimed at reducing post-harvest storage losses can also enhance resilience, in addition to promoting food availability. By encouraging more successful storage of commodities over the course of the year, they can improve intra-annual food security, making more food available during the 'lean season' (Aggarwal, Francis, and Robinson 2018; Kumar and Kalita 2017). Often new seeds are more vulnerable to pests and are therefore viewed as undesirable in the context of traditional grain storage. By overcoming these losses, improved storage technologies can enhance incentives for adoption of new seed technologies which, in turn can boost productivity (Omotilewa et al. 2018).

Development, dissemination and utilisation of agricultural big data:
Development of resilient and sustainable agriculture is also being facilitated by the big data initiative of the Consultative Group for International Agricultural Research (CGIAR), dubbed INSPIRE, https://bigdata.cgiar.org/inspire/, which seeks to harness recent advances in remote sensing, machine learning and robotics to support agricultural research and innovation in support of sustainable development and food security. These and other new scientific tools including precision biology (cell factories), combined with artificial intelligence. offer the prospect of making every element of the food system more efficient https://www.weforum.org/reports/innovation-with-a-purpose-the-role-of-technology-innovation-in-accelerating-food-systems-transformation. There is also an increasing emphasis on integrated systems approaches in which farming practices seek to imitate nature's ecological principles, whereby not only crops but also varied types of plants, animals, birds, fish, and other aquatic flora and fauna, are utilised for production.

Initiatives targeted at policy makers, researchers, agribusinesses need to be aligned with capacity development actions. This should seek to integrate knowledge generation with knowledge sharing in a manner that can effectively inform, and be informed by, action (Virji, (2012)). Farm households' decision-making in the context of risk and resilience challenges is often constrained by a lack of information on weather and market conditions. Many farmers in low-income countries rely on informal knowledge of local climates and weather patterns that has been acquired over decades or even centuries. The challenge posed for these households by climate change is that much of this knowledge base is effectively destroyed as it is rendered irrelevant under the new climatology (Quiggin and Horowitz 2003). In this context accurate weather forecasting is of critical importance to the farming community. Indeed, Gine, Townsend and Vickery (Gine, Townsend, and Vickery 2007) found that farmers in India with less access to risk-coping mechanisms invested more in acquiring accurate weather forecasts.

The usefulness of modern climate forecasts will depend on "developing focused knowledge about which forecast information is potentially useful for which recipients, about how these recipients process the information, and about the characteristics of effective information delivery systems and messages for meeting the needs of particular types of recipients" (Stern and Easterling 1999). An example where a close link between research and capacity building has been planned from the beginning is the West African Science Service Centre on Climate Change and Adaptive Land Use (WASCAL, https://wascal.org/) with human capital programmes comprising ten graduate schools closely linked to the respective research activities and research institutions. Close links between research activities and capacity building are also considered in other larger research programmes such as N2Africa which emphasises putting nitrogen fixation to work for smallholder farmers in Africa (https://www.n2africa.org/) as well as through the AgMIP (https://agmip.org/) regional studies in Africa, Asia and other parts of the world. While all of these programmes have achieved good progress, links among these programmes are under-developed and they would generate greater impact through coordinated research and funding activities at the national and international scales.

Enhanced equity in food systems:
The socio-economic and institutional context in which innovations are introduced is key for advancing equity in farming communities (Bayard, Jolly, and Shannon 2007). However, solutions aiming to enhance agricultural productivity often focus on technological innovations but do not necessarily consider social, economic, and gender disparities. Growing evidence suggests that agriculture innovations can affect women and men differently within households and communities due to differences in power, roles, and access to rights (Doss 2001; Beuchelt 2016). Equity in agri-food systems, including being inclusive and sensitive to gender and social inequalities, can contribute to improving productivity (Beuchelt 2016). Development policies must address challenges and knowledge gaps related to social justice issues, environmental equity, and economic equity for smallholder farmers. Such achievements are possible only in a policy environment that promotes context-specific pro-smallholder value chains with equal access to innovations, capacity building opportunities, and smallholder-friendly financing and investment, as well as policies that support productive social safety nets. The FAO and IFAD are collaborating to strengthen the capacity of the indigenous groups, women and rural youth. Five percent of the world population belongs to indigenous people (FAO 2018) and they are culturally unique and have unique resilience strategies and challenges. IFAD is also working on the 4Ps (public-private-producers-partnership) in the agricultural sector to provide an enabling environment as a strategic goal. Some examples of advancing equity in the context of smallholder agriculture including strengthening social protection systems (e.g. food banks, emergency food pantries, nutrition-sensitive cash-transfer programmes, etc.), as well as supporting grassroots activities dedicated to providing vulnerable populations with access to healthy and sustainable food.

Agro-ecology:
Other measures include direct use of saline waters for agriculture and food, feed, fibre production, along with efforts to increase productivity for marginal and or subsistence farms (International Center for Biosaline Agriculture). This has the potential to improve the food security of poor households in rural areas by increasing food supply, and reducing dependence on purchasing food in a context of high food price inflation. The UN Special Rapporteur on the Right to Food, Oliver De Schutter (2011), highlights in his report that marginal and or small-scale ecological farming is already very productive and can do even better. He calls for the use of agro-ecological methods to increase food production where the hungry live. Leveraging agriculture-ecosystem mutualism can improve productivity and may be more accessible and viable for marginalised or smallholder livelihoods than methods reliant on high agrochemical inputs (Seppelt et al. 2020). Eco-farming for food security can be expanded to include the matrix of adjacent wild land, given the importance of landscape complexity for agro-ecological functions such as pest management, pollination, soil and water quality (Tscharntke et al. 2005; Ricketts et al. 2008).

Transnational policy coordination:
In addition to providing sustainable incomes, the food system must ensure food safety along the entire food chain. For many low- and middle-income countries, rapid demographic and dietary changes, among others, are contributing to broader exposure of populations to food-borne hazards, stretching limited capacity to manage food safety risks. However, food safety receives relatively little policy attention and is under-resourced. Building resilience in such complex agri-food value chains calls for more significant and smarter investments in food safety management capacity, particularly in low- and middle-income countries. Comprehensive national food safety policies require cross-ministerial collaborations, spanning agriculture, industry, public health, domestic and international trade, science, technology and education, in the setting food quality and safety strategies and ensuring their governance. Policy implementation of the food quality and food safety system must include elements of quality control and quality assurance systems, food safety standards, risk analysis, diagnostic technology, and traceability systems. Proactive and effective surveillance and rapid response are also critical aspects of food safety systems' performance to tackle risks (Jaffee et al. 2019). Further, food safety systems are a critical ingredient of successful food export performance. Recognising this potential barrier, Thailand's food sector has worked closely with the U.S. Food and Drug Administration (FDA) to meet the Preventive Controls for Human Food (PCHF) regulation, thereby avoiding burdensome export restrictions.

The Permanent Interstates Committee for Drought Control in the Sahel, known as "CILSS," is an international organization established in 1973, consisting of 13 countries in the Sahel of West Africa. The mandate of CILSS is to address desertification and to improve food security in the Sahel. Over the years, CILSS has established itself as its member states' technical arms in the area of food security. Subsequently, the Economic Community of West African States (ECOEarWAS) entrusted CILSS to support member states in developing their National Agriculture Investment Plans. In addition, CILSS created the Sahelian Pesticide Committee, known as the "CSP," a common regulation for the registration of pesticides in CILSS member states to combine the expertise in pesticide evaluation and management to improve pesticide registration. In line with the Rotterdam Convention framework for the regulation of hazardous chemicals and pesticides in international trade. The CSP has the authority to issue full or provisional registrations as well as refusing registration of a specific pesticide product. Besides facilitating the Rotterdam Convention's agenda, this approach has entirely replaced national pesticide registration in individual CILSS member states.

Food safety policies:
Consumers also directly affect the safety of foods through their food handling and preparation practices. Poor hygienic practices in the home are responsible for between 30-40% of food-borne illness. Many countries invest in educating and informing the public about food safety as an important means of reducing food-borne illness. For example, the Bangladesh Food Safety Network developed a range of initiative and Information, Education and Communications (IEC) materials to enhance awareness of food hygiene and safety among targeted groups, household food preparers, school children, and street food vendors. Recently, the FAO has worked with public health and food safety authorities and with consumer bodies to assist in the design of public information/education programmes/campaigns, including the monitoring of their effectiveness. In addition, FAO assists in the development of appropriate messages for use in such programmes to facilitate behaviour, as well as to improve food hygiene practices in food service sector (FAO 2020a).

Policy coordination will be key in enhancing future food system resilience. Schipanski et al., (2016) proposed integrated strategies for fostering food system resilience across scales, including (a) integrating gender equity and social justice into food security research and initiatives, (b) increasing the use of ecological processes rather than external inputs for crop production, (c) fostering regionalised food distribution networks and waste reduction, and (d) linking human nutrition and agricultural production policies. Enhancing social-ecological links and fostering adaptive capacity are essential to cope with short-term volatility and longer-term global change pressures. Pingali et al., (2005) explores the linkages between food security and crisis in different contexts, outlining the policy and institutional conditions needed to manage food security during a crisis and rebuild the resilience of food systems. In the Sahel, CILSS has emerged as an important vehicle for regional policy coordination on matters of food security. In the context of wealthy nations, the Joint Programming Initiative (JPI) in the EU (https://ec.europa.eu/programmes/horizon2020/en/h2020-section/joint-programming-initiatives) has improved the harmonisation of research activities across countries of the EU. A prominent example in the domain of the Summit21 is the JPI FACCE (Food Security, Agriculture and Climate Change, https://www.faccejpi.net/en/FACCEJPI.htm) which is presently further developed to also link research to national and EU stakeholders including policy makers to better coordinate research and policies.

Increasing risk-informed investments at all levels (local, regional, national and international) are needed to improve food security and resilience of food systems to ensure food security and adequate nutrition. Public Private Partnerships (PPP) offer an important opportunity to leverage resources from the private sector. PPPs also bring in new technologies and innovation and they can facilitate risk-sharing. The Committee on World Food Security (CFS) established criteria for responsible agricultural investments in 2015. A recent review (Mangeni 2019) on the role played by PPPs in disseminating acceptable technology to farmers, explores the current state of the field, and details approaches and methods for the establishment and promotion of PPPs in sub-Saharan Africa.

Community organisation and local innovation:
Bann Samkha, a small community in northern Thailand, has faced severe drought, leading to food insecurity. They solved this problem through community water resource management, allowing them to attain self-sufficiency in rice production. However, the long distance between rice farms and the commercial rice mill led to high transport costs. To cope with this problem, a compact and highly efficient small-scale rice mill machine has been developed. This user-friendly machine proven highly suitable for rice milling in rural areas, allowing farmers to sell high-value milled rice instead of paddy rice. Furthermore, the community uses the rice straw to produce rice straw paper through an organic process. With local wisdom, the community has now created an 'eatable calendar' wherein each page of the calendar is embedded with seeds of the month that grow into plantlets after being watered. The rice straw paper and the eatable calendar production have brought more income and a sustainable economy to the community. This illustrates the potential for communities to create high-value, circular and sustainable bio-economies (Thangphisityothin 2020).

THE IMPORTANCE OF CONTEXT SPECIFICITY

Resilience interventions will have differential impacts depending on their agro-ecological context, cultural aspects, policies and institutional capacities. The determinants of access to safe and nutritious food vary widely, reinforcing the fact that solutions cannot be "one size fits all". An estimated 1.4 billion people live and work in marginal environments (Chen and Ravallion 2004). Vulnerability for safe and nutritious food looms over all agro-ecologies in the face of climate change and biodiversity loss, but the fragile agro-ecologies are the most vulnerable. These regions are highly populated and stricken by poverty, food, nutritional and social insecurity. Site specific agro-ecological solutions, along with access and tenure to land and other renewable natural resources, could contribute to economic viability, provide appropriate solutions to many of the environmental challenges and be socially inclusive, addressing rural employment and livelihoods. This is particularly relevant in parts of Africa, South and South East Asia and Latin America countries agriculture still accounts for as much as three-quarters of employment (Roser 2013). The adoption of promising agricultural technologies has been far from universal, and has remained particularly low among the poor (Freebairn 1995). As a result, the Green Revolution may actually have created new sources of food insecurity in marginal areas by targeting high potential areas and a handful of high-value crops grown there (wheat, rice, maize) (Pearse 1990; Shiva 1991; P. L. Pingali, Hossain, and Gerpacio 1997). However, Enhancing agricultural development for marginal farmers and smallholders can create strong links to the rest of the rural sector (Koonin 2006), both through hiring of extra local labour at peak farming times and through more favourable expenditure patterns for promoting growth of the local non-farm economy, including rural towns (IFAD, 2013).

Many coastal communities and small island states also face difficult economic conditions. However, in many cases the development of tourism can make a valuable contribution. Indeed, coral reef tourism is a critical, undervalued ecosystem service generating $36 billion in global revenue (Spalding et al. 2017). In many cases, local fisherman can convert their boats to tourism and boost their incomes. While coral reefs face an immediate threat from climate change, there is potential to make them more resilient by managing fishing effort (Hughes et al. 2007). More generally, the impacts of climate change and extreme events differ considerably across the planet (IPCC 2014). Resilience and vulnerability strongly depends on the ability to adapt to climate change which again depends of economic conditions (Wheeler and Braun 2013) with poorer, less diversified regions being more vulnerable (Reidsma and Ewert 2008).

CONCLUDING REMARKS

Several reports have addressed resilience of food systems from different perspectives considering different parts of the food system and contexts of food security challenges (Fan, Pandya-Lorch, and Yosef 2014).

As evident from these reports and other studies, including the present review, resilience has successfully been used as a conceptual framework to improve food security as well as vehicle for organising links among respective actors, agencies and institutions. In the present study we have particularly addressed the contributions of the resilience approach as outlined in Figure 2, with respect to addressing important trade-offs and synergies. From the range of reviewed studies several conclusions can be drawn:

- The resilience approach has been helpful in developing solutions for food security, considering at least two but often more capacities. However, primary emphasis in the reviewed programmes and initiatives is focused on the absorption, adaptation and anticipation capacities and less on prevention and transformation. These important aspects need to be more considered in future studies. None of the studies integrates all capacities.
- The resilience approach is helpful in addressing trade-offs and synergies. However, key trade-offs identified here demand more attention. Furthermore, systematic approaches for analysis of these trade-offs are often missing.
- The reviewed initiatives and programmes have been successful in developing solutions for food security for the specific challenges and contexts. However, links among these programmes are often not well developed and additional benefits can be obtained by greater investment in institutions to facilitate the exchange of tools, data, information and knowledge. Such links would generate greater impact through coordinated research and funding activities at the national and international levels and support the further development of the resilience approach.
- Most importantly, these examples clearly reveal that there is no single game-changing solution that solves the range of different food security challenges. Instead, operationalisation of the resilience concept to build food security will depend on the specific context of the food security challenge and the respective actors involved. Hence, using resilience as a systems approach to support the conceptualisation of the food security challenge and the integration of actors, organisations and agencies to develop context-specific solutions offers a promising way forward.

REFERENCES

1. Aggarwal, S., E. Francis, and J. Robinson. 2018. “Grain Today, Gain Tomorrow: Evidence from a Storage Experiment with Savings Clubs in Kenya.” Journal of Development Economics 134 (September): 1–15. https://doi.org/10.1016/j.jdeveco.2018.04.001.
2. Ali, Zakari, Rosemary Green, Robert B. Zougmoré, Siyabusa Mkuhlani, Amanda Palazzo, Andrew M. Prentice, Andy Haines, Alan D. Dangour, and Pauline F. D. Scheelbeek. 2020. “Long-Term Impact of West African Food System Responses to COVID-19.” Nature Food 1 (12): 768–70. https://doi.org/10.1038/s43016-020-00191-8.
3. Alonso, Silvia, Paula Dominguez-Salas, and Delia Grace. 2019. “The Role of Livestock Products for Nutrition in the First 1,000 Days of Life.” Animal Frontiers 9 (4): 24–31. https://doi.org/10.1093/af/vfz033.
4. Ayanlade, Ayansina, and Maren Radeny. 2020. “COVID-19 and Food Security in Sub-Saharan Africa: Implications of Lockdown during Agricultural Planting Seasons.” Npj Science of Food 4 (1): 13. https://doi.org/10.1038/s41538-020-00073-0.
5. Babu, Suresh Chandra, and Sylvia Blom. 2014. “Capacity Development for Resilient Food Systems: Issues, Approaches, and Knowledge Gaps:” 6. 2020 Conference Papers. 2020 Conference Papers. International Food Policy Research Institute (IFPRI). https://ideas.repec.org/p/fpr/2020cp/6.html.
6. Baldos, U.L.C., and T.W. Hertel. 2015. “The Role of International Trade in Managing Food Security Risks from Climate Change.” Food Security 7 (2): 275–90. https://doi.org/10.1007/s12571-015-0435-z.
7. Barbier, Edward B. 2010. “Poverty, Development, and Environment.” Environment and Development Economics 15 (6): 635–60. https://doi.org/10.1017/S1355770X1000032X.
8. Barbier, Edward B., and Jacob P. Hochard. 2019. “Poverty-Environment Traps.” Environmental and Resource Economics, August. https://doi.org/10.1007/s10640-019-00366-3.
9. Barrett, Christopher B., and Mark A. Constas. 2014. “Toward a Theory of Resilience for International Development Applications.” Proceedings of the National Academy of Sciences of the United States of America 111 (40): 14625–30. https://doi.org/10.1073/pnas.1320880111.
10. Bayard, Burdy, Curtis M. Jolly, and Dennis A. Shannon. 2007. “The Economics of Adoption and Management of Alley Cropping in Haiti.” Journal of Environmental Management 84 (1): 62–70. https://doi.org/doi.org/10.1016/j.jenvman.2006.05.001.

11. Béné, Christophe. 2020. “Resilience of Local Food Systems and Links to Food Security – A Review of Some Important Concepts in the Context of COVID-19 and Other Shocks.” Food Security 12 (4): 805–22. https://doi.org/10.1007/s12571-020-01076-1.
12. Béné, Christophe, Peter Oosterveer, Lea Lamotte, Inge D Brouwer, Stef de Haan, Steve D Prager, Elise F Talsma, and Colin K Khoury. 2019. “When Food Systems Meet Sustainability – Current Narratives and Implications for Actions.” World Development, 15.
13. Beuchelt, Tina D. 2016. “Gender, Social Equity and Innovations in Smallholder Farming Systems: Pitfalls and Pathways.” In Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development, 181–98. SpringerOpen.
14. Binswanger-Mkhize, Hans P. 2012. “Is There Too Much Hype about Index-Based Agricultural Insurance?” Journal of Development Studies 48 (2): 187–200. https://doi.org/10.1080/00220388.2011.625411.
15. Blay-Palmer, Alison, Guido Santini, Marielle Dubbeling, Henk Renting, Makiko Taguchi, and Thierry Giordano. 2018. “Validating the City Region Food System Approach: Enacting Inclusive, Transformational City Region Food Systems,” 23.
16. Burgess, Robin, and Dave Donaldson. 2010. “Can Openness Mitigate the Effects of Weather Shocks? Evidence from India’s Famine Era.” American Economic Review 100 (2): 449–53. https://doi.org/10.1257/aer.100.2.449.
17. Calderone, Margherita, Derek Headey, and Jean-Francois Maystadt. 2014. “Resilience to Climate-Induced Conflict in the Horn of Africa.” In Resilience for Food and Nutrition Security. Washington D.C.: IFPRI. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/128445/.
18. CCAFS. 2015. “Scaling up Index Insurance for Smallholder Farmers: Recent Evidence and Insights.” CGIAR. https://ccafs.cgiar.org/resources/publications/scaling-index-insurance-smallholder-farmers-recent-evidence-and.
19. Chen, S., and M. Ravallion. 2004. “How Have the World’s Poorest Fared since the Early 1980s?” The World Bank Research Observer 19 (2): 141–69.
20. Dey, Madan, Patrick Kambewa, Mark Prein, Daniel Jamu, F Paraguas, Diemuth Pemsl, and Roehlano Briones. 2007. “Fish WorldFish Centre. Impact of the Development and Dissemination of Integrated Aquaculture–Agriculture Technologies in Malawi.” In , 118–46.
21. Doss, Cheyrl R. 2001. “Designing Agricultural Technology for African Women Farmers: Lessons from 25 Years of Experience.” World Development 29 (12): 2075–92. https://doi.org/doi.org/10.1016/S0305-750X(01)00088-2.
22. Dror, Shany, Franziska Harich, Orawan Duangphakdee, Tommaso Savini, Ákos Pogány, John Roberts, Jessica Geheran, and Anna C. Treydte. 2020. “Are Asian Elephants Afraid of Honeybees? Experimental Studies in Northern Thailand.” Mammalian Biology 100 (4): 355–63. https://doi.org/10.1007/s42991-020-00042-w.
23. Eshel, G., A. Shepon, T. Makov, and R. Milo. 2014. “Land, Irrigation Water, Greenhouse Gas, and Reactive Nitrogen Burdens of Meat, Eggs, and Dairy Production in the United States.” Proceedings of the National Academy of Sciences 111 (33): 11996–1. https://doi.org/10.1073/pnas.1402183111.
24. Fan, Shenggen, Rajul Pandya-Lorch, and Sivan Yosef. 2014. “Resilience for Food and Nutrition Security.” 0 ed. Washington, DC: International Food Policy Research Institute. https://doi.org/10.2499/9780896296787.
25. FAO. 2016. “Livestock in Protracted Crises : FAO in Emergencies.” Guidance Note. Rome: FAO. http://www.fao.org/emergencies/resources/documents/resources-detail/en/c/461428/.
26. ———, ed. 2017. Building Resilience for Food and Food Security. The State of Food Security and Nutrition in the World 2017. Rome: FAO.
27. ———. 2018. “Report on the Work of the FAO Indigenous Peoples Team.” http://www.fao.org/fileadmin/user_upload/faoweb/2018-New/Our_Pillars/2018_Annual_Report_FAO_Indigenous_Peoples_Team.pdf.
28. ———. 2020a. “Consumer Awareness: Improving Food Safety in Bangladesh.” 2020. http://www.fao.org/in-action/food-safety-bangladesh/activities/consumer-awareness/en/.
29. ———. 2020b. “The State of Food Security and Nutrition in the World 2020 | FAO | Food and Agriculture Organization of the United Nations.” FAO. https://doi.org/10.4060/CA9692EN.
30. FAO and WFP. 2020. FAO-WFP Early Warning Analysis of Acute Food Insecurity Hotspots: July 2020. Rome, Italy: FAO and WFP. https://doi.org/10.4060/cb0258en.
31. Folke, Carl. 2016. “Resilience (Republished).” Ecology and Society 21 (4). https://doi.org/10.5751/ES-09088-210444.
32. Freebairn, Donald K. 1995. “Did the Green Revolution Concentrate Incomes? A Quantitative Study of Research Reports.” World Development 23 (2): 265–79. https://doi.org/10.1016/0305-750X(94)00116-G.
33. Funk, Chris, Shraddhanand Shukla, Wassila Mamadou Thiaw, James Rowland, Andrew Hoell, Amy

McNally, Gregory Husak, et al. 2019. “Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security.” Bulletin of the American Meteorological Society 100 (6): 1011–27. https://doi.org/10.1175/BAMS-D-17-0233.1.

34. Gelo, Dambala, Edwin Muchapondwa, Abebe Shimeles, and Johane Dikgang. 2020. “Aid, Collective Action and Benefits to Smallholders: Evaluating the World Food Program’s Purchase for Progress Pilot.” Food Policy 97 (December): 101911. https://doi.org/10.1016/j.foodpol.2020.101911.
35. Gine, X., R. M Townsend, and J. Vickery. 2007. “Rational Expectations? Evidence from Planting Decisions in Semi-Arid India.” Working Paper, The World Bank (DECRG), University of Chicago and Federal Reserve Bank of New York FED. Google Scholar.
36. Gine, X., R. Townsend, and J. Vickery. 2008. “Patterns of Rainfall Insurance Participation in Rural India.” The World Bank Economic Review 22 (3): 539.
37. Gouel, Christophe, and David Laborde. 2018. “The Crucial Role of International Trade in Adaptation to Climate Change.” Working Paper 25221. National Bureau of Economic Research. https://doi.org/10.3386/w25221.
38. Gray, Leslie C, and William G Moseley. 2005. “A Geographical Perspective on Poverty-Environment Interactions.” The Geographical Journal 171 (1): 9–23. https://doi.org/10.1111/j.1475-4959.2005.00146.x.
39. Gurung, Ghana S, and Michael Kollmair. 2005. “Marginality: Concepts and Their Limitations, IP6 Working Paper No. 4.” University of Zurich, Winterthurerstr.
40. Hazell, Peter B. R., J. Anderson, N. Balzer, A. H. Clemmensen, U. Hess, and F. Rispoli. 2010. The Potential for Scale and Sustainability in Weather Index Insurance for Agriculture and Rural Livelihoods. Rome, Itally: IFAD-WFP. /paper/The-Potential-for-Scale-and-Sustainability-in-Index-Hazell-Anderson/f4edc50de49fb13bee390a01a326e72f07b8a6b8.
41. High Level Panel of Experts. 2020. “Impacts of COVID-19 on Food Security and Nutrition: Developing Effective Policy Responses to Address the Hunger and Malnutrition Pandemic.” Issue Paper. Rome: Committe on World Food Security: High Level Panel of Experts.
42. Hirvonen, Kalle, Alan de Brauw, and Gashaw T. Abate. 2021. “Food Consumption and Food Security during the COVID-19 Pandemic in Addis Ababa.” American Journal of Agricultural Economics, no. February. https://doi.org/10.1111/ajae.12206.
43. Holling, C S. 1973. “Resilience and Stability of Ecological Systems.” Annual Review of Ecology and Systematics 4 (1): 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245.
44. Hsiang, Solomon M., Marshall Burke, and Edward Miguel. 2013. “Quantifying the Influence of Climate on Human Conflict.” Science 341 (6151). https://doi.org/10.1126/science.1235367.
45. Hughes, Terence P., Maria J. Rodrigues, David R. Bellwood, Daniela Ceccarelli, Ove Hoegh-Guldberg, Laurence McCook, Natalie Moltschaniwskyj, Morgan S. Pratchett, Robert S. Steneck, and Bette Willis. 2007. “Phase Shifts, Herbivory, and the Resilience of Coral Reefs to Climate Change.” Current Biology 17 (4): 360–65. https://doi.org/10.1016/j.cub.2006.12.049.
46. Huguet, Jerrold W and Aphichat Chamratrithirong. 2011. Thailand Migration Report: Migration for Development in Thailand : Overview and Tools for Policymakers. Bangkok, Thailand: International Organization for Migration, Thailand Office.
47. IFAD. 2013. “Smallholders, Food Security, and the Environment.” International Fund for Agricultural Development: Rome.
48. IPCC. 2014. “Climate Change 2014: Impacts, Adaptation, and Vulnerability.” In Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
49. Jaffee, Steven, Spencer Henson, Laurian Unnivehr, Delia Grace, and Emilie Cassou. 2019. “The Safe Food Imperative: Accelerating Progress in Low- and Middle-Income Countries. Agriculture and Food Series. Washington, DC: World Bank. Doi:10.1596/978-1-4648-1345-0. License: Creative Commons Attribution CC BY 3.0 IGO.”
50. Jansen, Marion. 2020. “COVID-19 and the Global Economy.” In COVID-19 and the Global Economy. Virtual.
51. Kellet, Jan, and Dan Sparks. 2012. “Disaster Risk Reduction: Spending Where It Should Count.” Briefing Paper. https://devinit.org/resources/disaster-risk-reduction-spending-where-it-should-count/.
52. Klassen, Susanna, and Sophia Murphy. 2020. “Equity as Both a Means and an End: Lessons for Resilient Food Systems from COVID-19.” World Development 136 (December): 105104. https://doi.org/10.1016/j.worlddev.2020.105104.
53. Kongsager, Rico. 2018. “Linking Climate Change Adaptation and Mitigation: A Review with Evidence from the Land-Use Sectors.” Land 7 (4): 158. https://doi.org/10.3390/land7040158.
54. Koonin, S. E. 2006. “Getting Serious about Biofuels.” Science 311: 435–36.

55. Kumar, Deepak, and Prasanta Kalita. 2017. "Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries." Foods 6 (1). https://doi.org/10.3390/foods6010008.
56. Laborde, David, Will Martin, Johan Swinnen, and Rob Vos. 2020. "COVID-19 Risks to Global Food Security." Science 369 (6503): 500–502. https://doi.org/10.1126/science.abc4765.
57. Laborde, David, Will Martin, and Rob Vos. 2020. "Impacts of COVID-19 on Global Poverty, Food Security and Diets." Agricultural Economics Forthcoming.
58. Leat, Philip, and Cesar Revoredo-Giha. 2013. "Risk and Resilience in Agri-Food Supply Chains: The 404 Case of the ASDA PorkLink Supply Chain in Scotland." Supply Chain Management: An International Journal 18 (2): 219–213.
59. Lipper, Leslie, Philip Thornton, Bruce M. Campbell, Tobias Baedeker, Ademola Braimoh, Martin Bwalya, Patrick Caron, et al. 2014. "Climate-Smart Agriculture for Food Security." Nature Climate Change 4 (12): 1068–72. https://doi.org/10.1038/nclimate2437.
60. Mahajan, Kanika, and Shekhar Tomar. 2020. "COVID-19 and Supply Chain Disruption: Evidence from Food Markets in India." American Journal of Agricultural Economics n/a (n/a). https://doi.org/10.1111/ajae.12158.
61. Mangeni, Bonphace. 2019. "The Role of Public-Private Partnerships (PPP) in Ensuring Technology Access for Farmers in Sub-Saharan Africa." African Journal of Food, Agriculture, Nutrition and Development 19 (February): 14137–55. https://doi.org/10.18697/ajfand.84.BLFB1018.
62. Manning, Louise, and Jan Mei Soon. 2016. "Building Strategic Resilience in Food Supply Chain." Brithish Food Journal 118 (6): 1477 – 1493. https://doi.org/doi.org/10.1108/BFJ-10-2015-0350.
63. Martin, Will, and Kym Anderson. 2012. "Export Restrictions and Price Insulation During Commodity Price Booms." American Journal of Agricultural Economics 94 (2): 422–27. https://doi.org/10.1093/ajae/aar105.
64. Maystadt, Jean-François, Margherita Calderone, and Liangzhi You. 2015. "Local Warming and Violent Conflict in North and South Sudan." Journal of Economic Geography 15 (3): 649–71.
65. Molden, David, Karen Frenken, Randolph Barker, Charlotte de Fraiture, Bancy Mati, Mark Svendsen, Claudia Sadoff, and C. Max Finlayson. 2007. "Trends in Water and Agricultural Development." In Water for Food, Water for Life, edited by David Molden, 57–89. Colombo, Sri Lanka: EarthScan London and International Water Management Institute.
66. Mushtaq, Shahbaz, Jarrod Kath, Roger Stone, Ross Henry, Peter Läderach, Kathryn Reardon-Smith, David Cobon, et al. 2020. "Creating Positive Synergies between Risk Management and Transfer to Accelerate Food System Climate Resilience." Climatic Change 161 (3): 465–78. https://doi.org/10.1007/s10584-020-02679-5.
67. Narayanan, Sudha, and Shree Saha. 2020. "Urban Food Markets and the Lockdown in India." SSRN Scholarly Paper ID 3599102. Rochester, NY: Social Science Research Network. https://doi.org/10.2139/ssrn.3599102.
68. OECD. 2020. Strengthening Agricultural Resilience in the Face of Multiple Risks. Paris: OECD Publishing. https://doi.org/10.1787/2250453e-en.
69. Oliver De Schutter. 2011. "Report on the Right to Food. UN Human Rights Council." Online at <http://Rs.Resalliance.Org/?P=4612. http://rs.resalliance.org/?p=4612.
70. Omotilewa, Oluwatoba J., Jacob Ricker-Gilbert, John Herbert Ainembabazi, and Gerald E. Shively. 2018. "Does Improved Storage Technology Promote Modern Input Use and Food Security? Evidence from a Randomized Trial in Uganda." Journal of Development Economics 135 (November): 176–98. https://doi.org/10.1016/j.jdeveco.2018.07.006.
71. Paloma, Sergio Gomez y, Laura Riesgo, and Kamel Louhichi. 2020. The Role of Smallholder Farms in Food and Nutrition Security. doi.org/10.1007/978-3-030-42148-9.
72. Pearse, A. 1990. Seeds of Plenty Seeds of Want: Social and Economic Implications of the Green Revolution. Oxford University Press: New York.
73. Peters, Katie, David Keen, and Tom Mitchell. 2013. "When Disasters and Conflicts Collide: Improving Links between Disaster Resilience and Conflict Prevention." Overseas Development Institute: London. https://www.odi.org/publications/7257-disasters-conflicts-collide-improving-links-between-disaster-resilience-conflict-prevention.
74. Pingali, P.L., M. Hossain, and R.V. Gerpacio. 1997. "Asian Rice Bowls: The Returning Crisis." CAB International: Wallinford.
75. Pingali, Prabhu, Luca Alinovi, and Jacky Sutton. 2005. "Food Security in Complex Emergencies: Enhancing Food System Resilience: Food Security in Complex Emergencies: Enhancing Food System Resilience." Disasters 29 (June): S5–24. https://doi.org/10.1111/j.0361-3666.2005.00282.x.
76. Quiggin, J., and J. Horowitz. 2003. "Costs of Adjustment to Climate Change." The Australian Journal of Agricultural and Resource Economics 47 (4): 429–46.
77. Reiche, M., N. Azzu, A. Bogdanski, S. Braatz, S. Bunning, V. Evtimov, Michelle Gauthier, et al. 2012.

"Mainstreaming Climate Smart Agriculture into a Broader Landscape Approach." Rome, Italy: FAO. /paper/MAINSTREAMING-CLIMATE-SMART-AGRICULTURE-INTO-A-Reiche-Azzu/ee0a42a4feca1698a933b50c4eb6492a35fede01.
78. Reidsma, P., and F. Ewert. 2008. "Regional Farm Diversity Can Reduce Vulnerability of Food Production to Climate Change." Ecology and Society 13 (1). https://doi.org/10.5751/es-02476-130138.
79. Ricketts, Taylor H., James Regetz, Ingolf Steffan-Dewenter, Saul A. Cunningham, Claire Kremen, Anne Bogdanski, Barbara Gemmill-Herren, et al. 2008. "Landscape Effects on Crop Pollination Services: Are There General Patterns?" Ecology Letters 11 (5): 499–515. https://doi.org/10.1111/j.1461-0248.2008.01157.x.
80. Roser, Max. 2013. "Employment in Agriculture." Our World in Data, April. https://ourworldindata.org/employment-in-agriculture.
81. Schipanski, Meagan, Graham Macdonold, Steven Roseenzweig, and Chappel. 2016. "Realizing Resilient Food Systems" 67: 11.
82. Schwarz, Anne-Maree, Christophe Béné, Gregory Bennett, Delvene Boso, Zelda Hilly, Chris Paul, Ronnie Posala, Stephen Sibiti, and Neil Andrew. 2011. "Vulnerability and Resilience of Remote Rural Communities to Shocks and Global Changes: Empirical Analysis from Solomon Islands." Global Environmental Change 21 (3): 1128–40. https://doi.org/10.1016/j.gloenvcha.2011.04.011.
83. Seppelt, Ralf, Channing Arndt, Michael Beckmann, Emily A. Martin, and Thomas W. Hertel. 2020. "Deciphering the Biodiversity–Production Mutualism in the Global Food Security Debate." Trends in Ecology & Evolution 0 (0). https://doi.org/10.1016/j.tree.2020.06.012.
84. Shaffer, L. Jen, Kapil K. Khadka, Jamon Van Den Hoek, and Kusum J. Naithani. 2019. "Human-Elephant Conflict: A Review of Current Management Strategies and Future Directions." Frontiers in Ecology and Evolution 6. https://doi.org/10.3389/fevo.2018.00235.
85. Shiva, V. 1991. "The Violence of the Green Revolution: Third World Agriculture, Ecology and Politics. T." Third World Network: Malaysia.
86. Spalding, Mark, Lauretta Burke, Spencer A. Wood, Joscelyne Ashpole, James Hutchison, and Philine zu Ermgassen. 2017. "Mapping the Global Value and Distribution of Coral Reef Tourism." Marine Policy 82 (August): 104–13. https://doi.org/10.1016/j.marpol.2017.05.014.
87. Sterly, Patrick Sakdapolrak and Harald. 2020. "Building Climate Resilience through Migration in Thailand." Migrationpolicy.Org. December 2, 2020. https://www.migrationpolicy.org/article/building-climate-resilience-through-migration-thailand.
88. Stern, P. C, and W. E Easterling. 1999. Making Climate Forecasts Matter. National Academies Press.
89. Tscharntke, Teja, Alexandra M. Klein, Andreas Kruess, Ingolf Steffan-Dewenter, and Carsten Thies. 2005. "Landscape Perspectives on Agricultural Intensification and Biodiversity – Ecosystem Service Management." Ecology Letters 8 (8): 857–74. https://doi.org/10.1111/j.1461-0248.2005.00782.x.
90. UN FAO. 2020. "Resilience : FAO in Emergencies." 2020. http://www.fao.org/emergencies/how-we-work/resilience/en/.
91. UN Office for Disaster Risk Reduction. 2019. Global Assessment Report on Disaster Risk Reduction : UN Office for Disaster Risk Reduction,. http://digitallibrary.un.org/record/3825375.
92. UN Secretary General. 2016. "Outcome of the World Humanitarian Summit." New York: UN.
93. UNISDR. 2015. "Disaster Risk Reduction and Resilience in the 2030 Agenda for Sustainable Development." New York: United Nations. https://www.undrr.org/publication/disaster-risk-reduction-and-resilience-2030-agenda-sustainable-development.
94. United Nations. 2020. "The UN Common Guidance on Helping Build Resilient Societies." New York. https://www.sparkblue.org/basic-page/un-common-guidance-helping-build-resilient-societies.
95. Virji, Hassan. 2012. "Capacity Building to Support Knowledge Systems for Resilient Development—Approaches, Actions, and Needs." Current Opinion in Environmental Sustainability, 7.
96. Walker, Patrick G. T., Charles Whittaker, Oliver J. Watson, Marc Baguelin, Peter Winskill, Arran Hamlet, Bimandra A. Djafaara, et al. 2020. "The Impact of COVID-19 and Strategies for Mitigation and Suppression in Low- and Middle-Income Countries." Science 369 (6502): 413–22. https://doi.org/10.1126/science.abc0035.
97. Walters, C. 1986. Adaptive Management of Renewable Resource. New York: Macmillan Publishing.
98. Webber, H., H. Kahiluoto, R. Rötter, and F. Ewert. 2014. "Enhancing Climate Resilience of Cropping Systems." In Climate Change Impact and Adaptation in Agricultural Systems, 167–85.
99. Wheeler, Tim, and Joachim von Braun. 2013. "Climate Change Impacts on Global Food Security." Science 341 (6145): 508–13. https://doi.org/10.1126/science.1239402.
100. Wiener, Jonathan B., and Alberto Alemanno. 2015. "The Future of International Regulatory Cooperation: TTIP as a Learning Process toward

a Global Policy Laboratory.” Law and Contemporary Problems 78 (4): 103.

101. Willett, Walter, Johan Rockström, Brent Loken, Marco Springmann, Tim Lang, Sonja Vermeulen, Tara Garnett, et al. 2019. “Food in the Anthropocene: The EAT–Lancet Commission on Healthy Diets from Sustainable Food Systems.” The Lancet 393 (10170): 447–92. https://doi.org/10.1016/S0140-6736(18)31788-4.
102. World Food Programme. 2020. “Global Report on Food Crises.” https://www.wfp.org/publications/2020-global-report-food-crises.
103. Ziliak, James P. 2020. “Food Hardship during the Covid-19 Pandemic and Great Recession.” Applied Economic Perspectives and Policy n/a (n/a). https://doi.org/10.1002/aepp.13099.

This Report was prepared by members of the Scientific Group bicc Bonn International Center for Conversion

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

ADDRESSING FOOD CRISES IN VIOLENT CONFLICTS

by Birgit Kemmerling, Conrad Schetter and Lars Wirkus

SUMMARY

Food insecurity and hunger continue to threaten the lives and livelihoods of millions of people. Many of today's food crises are linked to violent conflicts in various ways. The number of people affected by conflict-driven food crises increased from 74 million in 2018 to more than 77 million one year later, particularly in north-eastern Nigeria, South Sudan, Afghanistan, Syria and Yemen. The achievement of food security ending hunger and malnutrition and enabling sustainable agriculture production as addressed by Sustainable Development Goal (SDG) 2 of 'Zero Hunger' therefore largely depends on the progress made on SDG 16 in promoting peaceful and inclusive societies.

However, the severe food crises in the past decade have demonstrated the weaknesses to govern food (in)security in conflict settings. While national governments or belligerents are often unable or unwilling to respond adequately to food crises, humanitarian relief operations face the challenges of reaching those people most in need of food supply and simultaneously avoiding exacerbating the conflict. This has left many of the affected communities having to find their own responses to food insecurity. If food crises are to be ef-

ABOUT THE AUTHORS

Birgit Kemmerling, Senior Researcher, Bonn International Center for Conversion (BICC)

Conrad Schetter, Professor, Director Bonn International Center for Conversion (BICC)

Lars Wirkus, Head of Research Infrastructure and Data, Bonn International Center for Conversion (BICC)

fectively addressed, research and policy actions need to tackle both food crises and violent conflict.

RECOMMENDATIONS

Respect access to food as a human right: Any policy action needs to be based on the common understanding that access to food is a human right. Providing safe, continued and sufficient access to food is foremost the respective government's role. Every government should pursue preventive policies and take emergency measures to secure food equally for all parts of its population. If a government lacks the capacity to prevent or mitigate a food crisis, it should allow and facilitate relief operations as demanded by humanitarian law. Any government or warring faction that prohibits parts of the population from access to food needs to be sanctioned.

Build a bridge between humanitarian assistance, development and peacebuilding: Food assistance, if implemented well, plays a key role in mitigating the devastating effects of conflicts and contributing to peace. While short-term assistance needs to be based on sound conflict analysis and a better understanding of the structural factors that determine vulnerabilities, long-term food assistance should actively integrate peacebuilding approaches. In line with current debates of the humanitarian–development–peace (HDP) nexus, improving food security needs greater cooperation and coordination between actors in humanitarian assistance, development cooperation and peacebuilding.

Integrate local capacities: Conflict-affected populations adopt multiple strategies to secure food, and these depend on a multitude of factors such as the conflict context, intensity, and duration, an individual's situation, access to resources and support and governance. Local response mechanisms and capacities to food crises and conflict need to be better understood and best practices integrated into relief operations and national response strategies.

Improve the data situation and links to early action in conflict settings: While early warning systems for famine have advanced over the past decades, challenges remain in accessing data in conflict settings and linking them to early action. The development of an integrated platform combining early warning systems for famine and violent conflict could add important data and the missing link to assess famine, drought and conflict risk more comprehensively while advancing anticipatory humanitarian action in fragile and conflict-affected settings.

1. INTRODUCTION

Food insecurity remains one of the greatest global challenges. Since 2014, the number of people affected by hunger worldwide has been rising again: in 2019, almost 750 million people were exposed to extreme food insecurity (FAO et al., 2020), out of whom almost 135 million people in 55 countries or territories were classified as in crisis conditions or worse (IPC/CH Phase 3 or above). Violent conflicts undoubtedly play a decisive role in current food crises. In 2019, more than 77 million people in 22 countries were affected by conflict-driven food crises (FSIN, 2020). In addition, it is worth mentioning that violent conflicts have severe short- and long-term impacts on the nutrition status of children. [1]

Food insecurity and violent conflicts are mostly found in regions with a high degree of fragility. Africa is still most affected by food crises: 54 per cent of the population globally facing food crises or worse (IPC/CH Phase 3 or higher[2]) are located in Africa (Fig.1). In East Africa, particularly in South Sudan, armed conflicts, violent extremism, inter-communal violence and other localised tensions mainly affect peace and security. Further conflict-driven food crises have emerged in two other African regions: the Lake Chad Basin, comprising the borderlands of Cameroon, Chad, Niger and northern Nigeria, and the Central Sahel, affecting Burkina Faso, Mali and Niger (FSIN, 2020). In both areas, insecurity and jihadist groups' expansionist aspirations have led to massive violent incidents and displacement of populations, destruction or closure of basic social services, disruption or permanent breakdown of productive activities, markets and trade flows. In Asia and the Middle East region, 40 million people are affected by conflict-driven food crises, especially Yemen, Afghanistan, and Syrian Arab Republic, where political, social

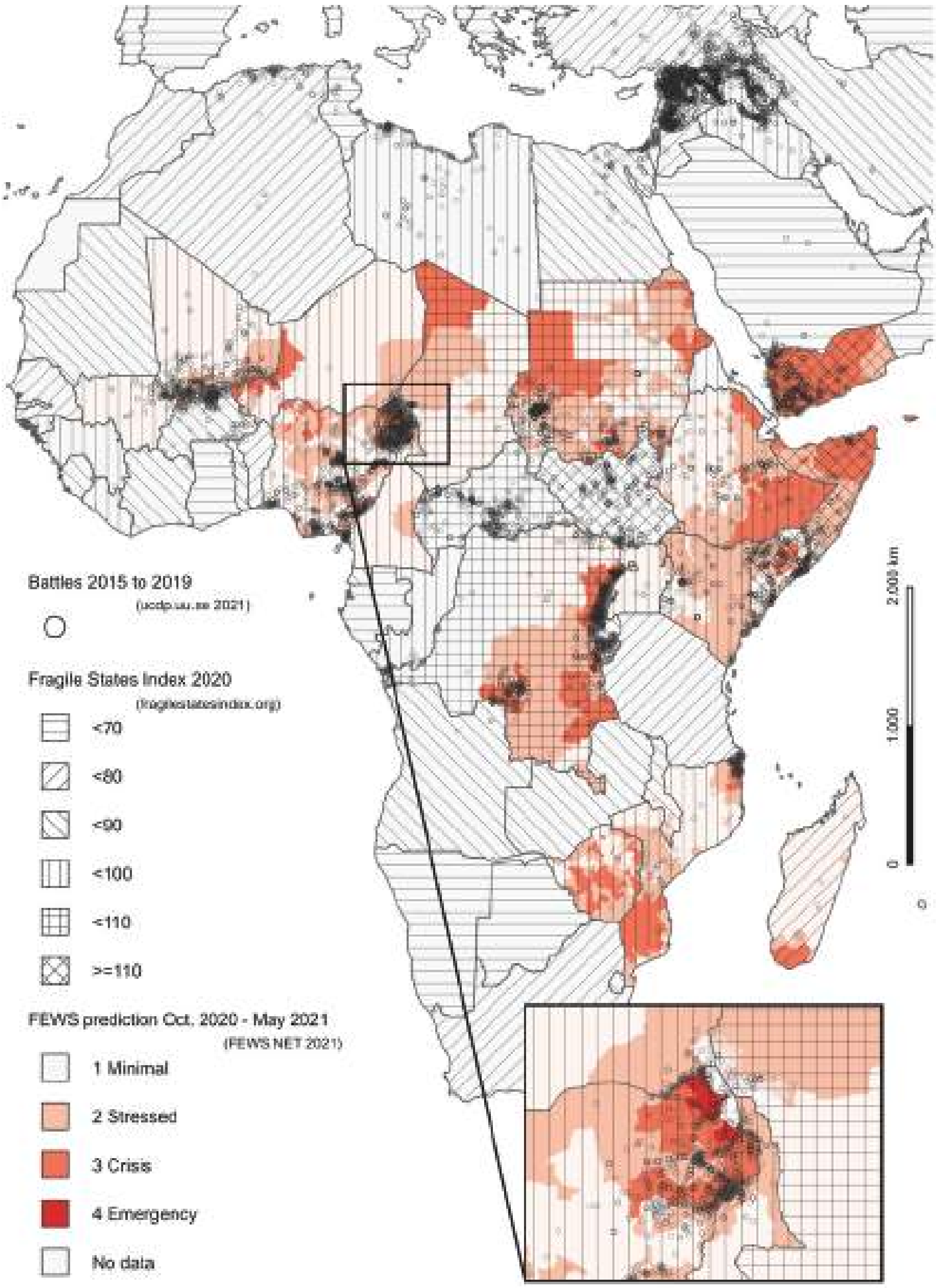
1 Studies in different contexts find evidence that conflict-affected children are shorter than children born in regions not affected by conflict. Moreover, negative effects on child weight at birth were observed if the mother was exposed to conflict during pregnancy. Physical and cognitive impacts have also been found in adults who were exposed to conflict in their early years (Brück et al., 2016).

2 IPC/CH Phase: Integrated Phase Classification is a standardised classification system to describe the anticipated severity of food emergencies / food insecurity according to a five-phase scale: minimal, stressed, crisis, emergency, famine. (https://fews.net/IPC)

and economic grievances or geopolitical tensions have sparked protracted violent and armed conflicts (FSIN, 2020).

This briefing paper looks at the multiple dimensions between current food crises and violent conflicts and identifies four key areas for a comprehensive response that addresses food insecurity and violent conflict.

Figure 1 Food insecurity, violent conflicts and fragility in Africa 2015–2021



Sources: Croicu, Mihai and Ralph Sundberg 2012; FAO 2021; FEWS.NET 2021; Messner et al. 2020.
Layout: Lars Wirkus, Vincent Glasow; BICC; April 2021.
The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by BICC.

2. MULTIPLE DIMENSIONS OF FOOD CRISES AND VIOLENT CONFLICTS

Over the past decade, a growing body of research has examined the mutual impact between violent conflicts and food insecurity (for an overview, see Brück et al., 2016; Martin-Shields & Stojetz, 2019) and indicated strong correlations on multiple layers. However, food insecurity, as well as violent conflicts, are characterised by a high degree of complexity and contextualisation. Thus, discussions about the state of food insecurity and the typology of violent conflicts tend to become objectives in themselves. Criteria for determining the state of food insecurity are usually based on the four dimensions of availability, access, stability and utilisation and encompass a range of variables covering different sectors such as health, food prices and agricultural production. Analyses of food security range from the individual to the global level, and are classified by severity (FSIN, 2020).

Typologies of violent conflict differentiate between the duration and intensity of violent conflicts, between root causes, key drivers, or ways of mobilisation as well as between domestic, regional and inter-state constellations (for an overview, see Demmers, 2016).[3] Each of these typologies entails a certain interpretation of violent conflicts. However, a categorisation of violent conflicts which centres on food (in)security is missing so far. To narrow this gap, we will link the logics of war to food (in)security. We will identify three dimensions of how violent conflicts have an impact on food (in)security.

2.1 Destruction and food insecurity

The general principle of violent conflicts is that belligerent parties aim to harm, defeat or even eliminate their 'enemy'. Consequently, the emergence of frontlines, battlefields and war zones is an inevitable effect of violent conflicts, even if the current technological upgrading of modern armies and warfare (e.g. drones) aims to increase the accuracy of military attacks (Prinz & Schetter, 2017). This is why by and large, violent interactions go hand in hand with physical destruction, affecting people's vulnerabilities in various ways.

In general, Collier (1999) finds that the gross domestic product (GDP) per capita declines at an annual rate of 2.2 per cent during civil wars.

Since the majority of people in many of today's conflict-affected countries depend on small-scale farming to provide food and income for their households, small-scale agriculture is particularly affected: the destruction (e.g. bombing) or contamination (e.g. land mines, chemical weapons) of agricultural areas, as well as infrastructure (irrigation networks, roads, bridges, buildings, etc.), might force farmers to abandon agriculture altogether. Farmers may also no longer be able to cultivate their fields for lack of access to seeds and fertiliser, credits and capital, due to the uncertainty of access to buyers and markets and the displacement or killing of people (Baumann & Kuemmerle, 2016).

Especially when the expansion of war zones provokes forced migration on a large scale, the impacts on food security are direct and severe, not only in the short term but often also in the long term. Forced migration not only leads to the collapse of agricultural production and infrastructure but also disrupts or interrupts local and regional supply chains and increases food prices on local markets. At the same time, displaced people have to give up their livelihoods as producers of food (farmers, pastoralists etc.) and are thus exposed to food insecurity themselves (Brück et al., 2016), especially if they become dependent on food aid from humanitarian organisations and cannot restart agricultural activities.

The rehabilitation of war zones for food production and food supply takes decades. Clearing battlefields (de-mining), re-building physical infrastructure and establishing operational governance structures is costly and takes time. Moreover, such phases of post-war reconstruction are overshadowed by fierce disputes over access to and ownership of land and water, as property rights often change hands in times of war (Van Leeuwen & Van Der Haar, 2016). Thus, food insecurity, for poor populations in particular, often persist beyond the end of a violent conflict.

2.2 Food (in)security and warring factions

Food supply is of strategic importance to any armed group, from large-scale armies to vigilant gangs (Justino & Stojetz, 2016). This is why armed groups' presence and rule directly impact local food security and the control of production areas. Historically, the supply of large armies with food went hand in hand with the plundering of food storages and the looting

3 The question of when a violent conflict can be labelled as ‚war' is still ongoing. Its definition in International Law (declaration of war) diverges from the one in Peace and Conflict Studies (e.g. number of causalities).

of civilian households and markets. Although looting is still a common strategy, the links between armed groups' presence and food security are more complex: armed groups might show a strong interest in local food production and other goods. Combatants can take direct control over agricultural resources and livestock for sustenance or levy taxes on these products. For example, in Syria and Iraq, the agrarian zones seized by Islamic State were maintained to a large extent, despite massive forced displacement (Eklund et al., 2017).

People in conflict-affected contexts also adjust their practices to changing politics and (local) political actors. To protect their livelihoods and food security, people might (voluntarily or coerced) cooperate with armed groups (Martin-Shields & Stojetz, 2019). On the one hand, individuals participate in and support armed groups because they may benefit from the conflict through improved economic opportunities, such as access to food, looting and appropriation of agricultural land or livestock (Keen, 1998). On the other, people, such as farmers in agricultural off-seasons, might be recruited as part-time fighters.

2.3 Hunger as a weapon

When violent conflicts are directed against certain social segments, food insecurity can become "a weapon of war" (Messer & Cohen, 2015), as either a direct strategy or a by-product. The goal is either to deprive a particular warring party of the population's support or eliminate entire population groups (ethnic cleansing, genocide). Direct strategies include cutting off food supplies to harm hostile armies and the population supporting them (De Waal, 2018). Similarly, blocking food access and destroying food infrastructure ("scorched earth") are calculated military techniques not only to ignite mass starvation, malnutrition and hunger among the population but also to foster forced migration. Although the number of victims of mass starvation has declined in the past decades, it is still a widely-used military strategy in ongoing conflict zones such as Yemen, Syria, South Sudan or the Central African Republic.

Strategies may also include preventing humanitarian access. In recent food crises, Al-Shabaab in Somalia, Islamic State in Syria or commanders in South Sudan refused aid from humanitarian agencies. Governments themselves often violate the humanitarian principle and reject international relief operations, especially if they form part of the conflict, as could be witnessed in Syria and Yemen. The bypassing of humanitarian principle can also extend to donor governments; one reason for the delayed response to the food crisis in Somalia in 2011 was the US anti-terrorist legislation, which made it difficult for humanitarian organisations to provide assistance to areas controlled by Al-Shabaab (De Waal, 2018).

We have shown how the three interrelated dimensions of war logics—destruction, rule of armed groups and hunger as a weapon—have multiple effects on people's food insecurity. However, other factors, such as (conflict-related) increases in food and seed prices as well as (changing) climatic conditions, often amplify the exposure to conflict and food insecurity (Martin-Shields & Stojetz, 2019). In many of today's conflict-affected countries, smallholder farmers, who are already vulnerable in the absence of conflicts (natural hazards) present a large part of the population. Conflict is an additional 'shock' that affects these populations' livelihoods and well-being (Brück et al, 2016). In times of war, natural hazards affect the population much harder and increase the difficulty of access to food dramatically. As the most severe natural hazards, droughts exacerbate the effect of food (in)security. Droughts as 'creeping' or slow-onset disasters usually affect larger land areas than other types of disasters and make mitigation and adaptation strategies difficult to implement. Many of the adverse effects of drought often accumulate slowly and may persist for years after the event has ended (Wirkus & Piereder, 2019).

What is less clear is whether food insecurity in turn sparks, intensifies or perpetuates conflict. While food insecurity alone is not likely to cause violent conflicts, it can increase social grievances in combination with socio-economic and political inequalities. These exclude parts of the population (particularly youth) from economic activities and participation in political decision-making processes, which ultimately can fuel civil unrest or conflicts (Brinkman & Hendrix, 2011; Vestby et al., 2018). Besides structural conditions, rising food prices have been found to exacerbate the risk of political unrest and conflicts, particularly in urban settings. The dominant explanation for the vicious circle of price and violent conflict are consumer grievances: higher prices create or increase economic constraints and/or sentiments of (perceived) relative deprivation, which activate grievances that, in turn, can lead to conflict (whereas conflict is likely to increase food prices again) (Raleigh et al., 2015). These grievances can be directed against the state if it fails to secure food for the population in the face of rising global food prices. In Africa, rising food prices and unrest were associated with more political repression (Berazneva & Lee, 2013).

3. ADDRESSING FOOD CRISES AND VIOLENT CONFLICT

The complex relationships between food crises and violent conflicts require comprehensive and adapted policy actions. These actions must refer to the reduction of food insecurity as an effect of violent conflict and consider the reduction of violent conflict or conflict risks itself. We thus suggest four key areas for a multi-faceted response that addresses food insecurity and violent conflict.

3.1 Respect access to food as a human right during violent conflict

Access to food is a human right. Any government should pursue preventive policies and take emergency measures to secure food equally for all parts of its population. If a government lacks the capacity to prevent or mitigate a food crisis, it should allow and facilitate relief operations as demanded by humanitarian law (Akande & Gillard, 2019). However, national governments or belligerents are often unable or unwilling to respond adequately to food crises. At the same time, international relief operations face the challenges of reaching the people most in need and of avoiding exacerbating the conflict.

Therefore, all actors must comply with the provisions to protect the population from intended starvation and with humanitarian principles to guarantee humanitarian access. Any government or warring faction that prohibits parts of the population from access to food needs to be sanctioned. UN Security Council Resolution 2417 is a major step in this direction. The Resolution stresses the importance of compliance by belligerents with international humanitarian law and condemns the denial of humanitarian access to affected civilians (UNSC, 2018). Most importantly, the Resolution stipulates that the obstruction of humanitarian access in conflict settings can result in targeted sanctions, as already used, for example, for Al-Shabaab in Somalia (Akande & Gillard, 2019). Thus, the Resolution has the potential to be used by UN agencies to monitor and report robustly on human-induced food crises in conflicts and call on the Security Council and the international community to act (Zappalà, 2019).

3.2 Build bridges between humanitarian action, development and peacebuilding

The genuine role of international relief operations in food crises is to prevent or alleviate human suffering induced by disasters and conflicts. Short-term food assistance during violent conflicts usually focuses on improving food consumption of conflict-affected people and communities. It also aims to support the most vulnerable, such as displaced persons, children, pregnant and nursing women. However, relief operations in conflict settings often face challenges in guaranteeing aid workers' safety and security, gaining necessary data of affected populations and reaching those people most in need in a timely and appropriate manner (see, for example, Tranchant et al., 2019). At the same time, food interventions risk becoming a source of conflict themselves, primarily because of an inadequate understanding of the conflict setting (Devereux, 2000). The misappropriation of food aid in particular, such as the usurpation of food by violent actors, can fuel political grievances and perpetuate conflict. Moreover, food aid can undermine local food production and markets and affect the development of local capacity (Hendrix & Brinkman, 2013). A clear and locally informed analysis of the conflict and its context as well as increased equity and accountability is needed to prevent negative impacts of food aid in conflict environments.

While short-term food aid focuses primarily on alleviating human suffering rather than resolving violent conflict, long-term humanitarian assistance, as provided particularly in protracted crises or post-conflict situations, can identify potential conflicts and address them, reducing the risk of conflict flare-ups. Usually, these interventions have a stronger impact than the immediate supply of food (or cash/vouchers) and already include development assistance measures. Long-term food assistance can therefore play a crucial role in building local capacity, restoring agricultural production and, ultimately, consolidating peace. However, it is crucial to initiate its provision early enough and consider the amounts needed. It is also vital that it reaches the people who need it most, such as internally-displayed persons (IDPs), host communities and returnees (Hendrix & Brinkman, 2013; Lander & Richards, 2019). Nevertheless, aid agencies need to be aware that the longer food aid is provided, the more it has a direct impact on the local food market and price trends. Therefore, nuanced planning and management are required to avoid affecting smallholders' livelihoods by flooding them with aid.

To effectively address these challenges, long-term food assistance needs to bridge humanitarian action, development intervention and peacebuilding. Thus, food assistance is a key instrument addressed in current debates of the humanitarian–development–peace (HDP) nexus, which calls for greater cooperation and coordination among actors in humanitarian aid, development cooperation and peacebuilding.

3.3 Integrate local capacities

Conflict-affected populations adopt very different strategies to secure food. These strategies depend on multiple factors such as the conflict context, intensity and duration, the individual situation, access to resources and support, and governance. For example, rather than aiming to maximise agricultural profits, farmers may change their crop production to a low-risk, low-return strategy by switching their production from cash crops to less profitable crops as these crops provide food for subsistence or can be easily transferred in case of displacement. However, maintaining these low-risk-low-return strategies after conflicts end affects their recovery and can further affect their livelihood in the long run (Arias et al., 2017).

Similarly, pastoralists may adapt livestock production to the conflict, e.g. by selling livestock to have sufficient cash or hiding livestock from armed groups or local ruling groups (Brück et al, 2016). Furthermore, studies have shown that households increase their use of safety nets to minimise uncertainty. Support ranges from cash transfers to in-kind assistance received by the household (Brück & d'Errico, 2019). Remittances are also an important safety net in responding to food crises and conflict but still much needs to be learned about its role for affected people (Haan et al., 2012). Therefore, local response mechanisms to food crises and conflicts need to be better understood and successfull practices incorporated into relief efforts and national response strategies while, at the same time, striving to avoid potential harm.

3.4 Improve the data situation and better link different data sets with early action

Early warning mechanisms for famine such as FEWS NET have advanced over the last 35 years towards better predicting and managing food crises. They provide decision-makers and relief organisations with a rigorous, evidence- and consensus-based analysis of food insecurity and acute malnutrition situations. However, several challenges remain. First, in violent conflicts, access to data needed for comprehensive analysis and timely warning is often restricted. Second, the announcement of a food emergency is highly political and often challenged by claims of sovereignty (Lander & Richards, 2019). Third, even if warnings are timely and allow careful planning, adequate finance mechanisms are often not in place. Recent developments in anticipatory action, such as FAO's Early Warning Early Action or ICRC's forecast-based financing approach, aim to close the gap between forecasting tools and delayed response but still face multiple challenges in adjusting these to food crises and conflict (Wagner & Jaime, 2020). Forth, a knowledge gap still exists between data that is available to assess the food security situation and data on conflict early warning. Conflict early warning and forecasting systems such as UCDP ViEWS, ACLED Pulse) address this knowledge dilemma. They have the potential to close the "conflict assessment gap" of current food crisis warning systems (Wirkus & Piereder, 2019).

An integrated platform developed to combine early warning data sets for famines and violent conflicts could provide a better basis for a more comprehensive assessment of famine, drought and conflict risk and advance anticipatory humanitarian action in fragile and conflict-affected settings.

Taking into account these four key areas could help national governments and international humanitarian and development organisations to take effective preventive, anticipatory and emergency action against food crises during violent conflict, while at the same time integrating peacebuilding approaches into long-term food interventions to address hunger and conflict.

REFERENCES

1. Akande, D. & Gillard, E. (2019). Conflict-induced food insecurity and the war crime of starvation of civilians as a method of warfare: The underlying rules of International Humanitarian Law. BSG Working Paper 2019/030. Accessed at https://www.bsg.ox.ac.uk/research/publications/conflict-induced-food-insecurity-and-war-crime-starvation-civilians-method
2. Arias, M. A., Ibáñez, A. M., & Zambrano, A. (2017). Agricultural production amid conflict: Separating the effects of conflict into shocks and uncertainty. HiCN Working Paper 245.
3. Baumann, M. & Kuemmerle, T. (2016). The impacts of warfare and armed conflict on land systems. Journal of Land Use Science 11, 672-688. https://doi.org/10.1080/1747423X.2016.1241317
4. Berazneva, J., & Lee, D. R. (2013). Explaining the African food riots of 2007-2008: An empirical analysis. Food Policy 39, 28–39. https://doi.org/10.1016/j.foodpol.2012.12.007
5. Brinkman, H. J., & Hendrix, C. S. (2011). Food insecurity and violent conflict: Causes, consequences, and addressing the challenges. Occasional Paper no. 24. Accessed at https://www.wfp.org/publications/occasional-paper-24-food-insecurity-and-violent-conflict-causes-consequences-and-addressing-
6. Brück, T., Habibi, N., Martin-Shields, C., Sneyers, A., Stojetz, W., & van Weezel, S., (2016). The relationship between food security and violent conflict. Report to the Food and Agriculture Organization. Final Report to FAO. Accessed at https://isdc.org/wp-content/uploads/2019/08/Food-Security-and-Conflict-2016-12-22.pdf
7. Brück, T., d'Errico, M., & Pietrelli, R. (2019). The effects of violent conflict on household resilience and food security: Evidence from the 2014 Gaza conflict. World Development 119, 150-164.
8. Collier, P. (1999). On the economic consequences of civil war. Oxford Economic Papers 51.
9. De Waal, A. (2018). The end of famine? Prospects for the elimination of mass starvation by political action. Political Geography 62, 184-195. https://doi.org/10.1016/j.polgeo.2017.09.004
10. Demmers, J. (2016). Theories of violent conflict: An introduction. London: Routledge.
11. Devereux, S. (2000). Famine in the twentieth century. IDS working papers issue 105.
12. Eklund, L., Degerald, M., Brandt, M., Prishchepov, A.V., & Pilesjö, P. (2017). How conflict affects land use: agricultural activity in areas seized by the Islamic State. Environmental Research Letters, 12(5), 1-10. https://doi.org/10.1088/1748-9326/aa673a
13. FAO, IFAD, UNICEF, WFP & WHO. (2020). The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. Rome, FAO. https://doi.org/10.4060/ca9692en
14. FSIN. (2020). Global report on food crises. Joint analysis for better decisions. Accessed at https://www.wfp.org/publications/2020-global-report-food-crises
15. Haan, N., Devereux, S., & Maxwell, D. (2012). Global implications of Somalia 2011 for famine prevention, mitigation and response. Global Food Security 1(1), 74-79. http://dx.doi.org/10.1016/j.gfs.2012.09.003
16. Hendrix, C. & Brinkman, H. (2013). Food Insecurity and Conflict Dynamics: Causal Linkages and Complex Feedbacks. Stability: International Journal of Security & Development 2(2), 1-18. http://dx.doi.org/10.5334/sta.bm
17. Justino, P. & Stojetz, W. (2018). On the legacies of wartime governance (HiCN Working Paper 263).
18. Keen, David. (1998). The economic functions of violence in civil wars. Oxford University Press for the International Institute for Strategic Studies.
19. Lander, B. & Richards, R. V. (2019). Addressing hunger and starvation in situations of armed conflict – Laying the foundations for peace. Journal of International Criminal Justice 17(4), 675-698. https://doi.org/10.1093/jicj/mqz055
20. Martin-Shields, C. P., & Stojetz, W. (2019). Food security and conflict: Empirical challenges and future opportunities for researchand policy making on food security and conflict. World Development 119, 150-164. https://doi.org/10.1016/j.worlddev.2018.07.011
21. Messer, E. & Cohen M. J. (2015). Breaking the links between conflict and hunger redux. Special Issue: Global Food Security and Health, 7(3), 211-233. https://doi.org/10.1002/wmh3.147
22. Prinz, J., & Schetter, C. (2017). Conditioned sovereignty: The creation and legitimation of spaces of violence in counterterrorism operations of the "war on terror". Alternatives, 41(3), 119-136.
23. Raleigh, C., Choi, H. J. & Kniveton, C. (2015). The devil is in the details: An investigation of the relationships between conflict, food price and climate across Africa. Global Environmental Change 32, 187-199, https://doi.org/10.1016/j.gloenvcha.2015.03.005
24. Tranchant, J. P., Gelli, A., Bliznashka, L., Diallo, A. S., Sacko, M., Assima, A., Siegel, E. H., Aurino, E., & Masset, E. (2019). The impact of food assistance on food insecure populations during conflict: Evidence from a quasi-experiment in Mali. World Development 119, 185-202. https://doi.org/10.1016/j.worlddev.2018.01.027

25. UNSC (2018). Security Council resolution 2417 (2018) [on conflict-induced food insecurity] / adopted by the Security Council at its 8267th meeting, on 24 May 2018. Accessed at https://digitallibrary.un.org/record/1627380?ln=en
26. Van Leeuwen, M. & Van Der Haar, G. (2016). Theorizing the land–violent conflict nexus. World Development, 78, 94-104. https://doi.org/10.1016/j.worlddev.2015.10.011
27. Vestby, J., Rudolfsen, I., & Buhaug, H. (2018). Does hunger cause conflict? Peace Research Institute Oslo – Climate & Conflict, 18 May 2018. Accessed at https://blogs.prio.org/ClimateAndConflict/2018/05/does-hunger-cause-conflict/
28. Wagner, M. & Jaime, C. (2020). An agenda for expanding forecast-based action to situations of conflict. GPPi Working Paper. Accessed at https://www.gppi.net/media/Wagner_Jaime_2020_Forecast-Based-Action-in-Conflicts.pdf
29. Wirkus, L., & Piereder, J. (2019). Early warning systems for drought and violent conflict – toward potential cross-pollination. In E. Mapedza, D. Tsegai, M. Bruntrup, & R. Mcleman (Eds.), Drought challenges: Policy options for developing countries (pp. 165-181). Current directions in water scarcity research, Vol. 2. Amsterdam: Elsevier.
30. Zappalà, S. (2019). Conflict Related Hunger, 'Starvation Crimes' and UN Security Council Resolution 2417 (2018). Journal of International Criminal Justice 17(4), 881-906. https://doi.org/10.1093/jicj/mqz047

The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by the Scientific Group for the Food Systems Summit
July 2021

BOOST NATURE-POSITIVE PRODUCTION
A PAPER ON ACTION TRACK 3

by Elizabeth Hodson, Urs Niggli, Kaoru Kitajima, Rattan Lal and Claudia Sadoff

ABSTRACT

Transforming food systems involves five action tracks: i) access to safe and nutritious food, ii) sustainable consumption, iii) nature-positive production, iv) equitable livelihood, and v) resilience to shocks and stress. The overall goal of Action Track 3 is to reconcile the need for the production system to meet the demands from growing populations and rising prosperity with the necessity of restoring the environment, improving the

ABOUT THE AUTHORS

Elizabeth Hodson de Jaramillo (Colombia) Professor Em. School of Sciences of the Pontificia Universidad Javeriana, and member of Inter American Network of Academies of Sciences (IANAS).

Urs Niggli (Switzerland) Scientist focusing on sustainable farming systems, from 1990 to 2020 he led the Research Institute of Organic Agriculture (FiBL).

Claudia Sadoff (USA) Executive Management Team Convener and Managing Director, Research Delivery and Impact, of the Consultative Group on International Agricultural Research

Kaoru Kitajima (Japan) Professor at Kyoto University Graduate School of Agriculture; a forest ecologist, especially in tropical America and Asia.

Rattan Lal (USA) Distinguished University Professor of Soil Science, Director CFAES Rattan Lal Center for Carbon Management and Sequestration at the Ohio State University. World Food Prize Laureate 2020

quality of soil, conserving biodiversity, and sustainably managing land, water and other natural resources. The strategy is to protect, manage and restore ecosystems: to "produce more from less" and set aside some land and water for nature. In this context, action at the landscape scale is key, extending beyond individual production fields to the watershed, entire river basin, and the coastal area influenced by the change of land use and river discharges (IPCC 2019). Nature-positive landscape-level interventions include system-based conservation agriculture, agroforestry, river basin management, bio-inputs, integrated soil fertility management, soil and water conservation and nutrient recycling. In particular, maintaining trees in landscapes, avoiding deforestation and promoting landscape restoration are critically important for preventing soil erosion, regulating water resources, and protecting environmental services essential for sustaining production at multiple scales from regional to global. Such nature-positive approaches are best based on bottom-up and territorial processes, strengthened by scientific innovations and enabling policy environments. Translating science into transformative action also requires system-level governance and policy interventions that enable and provide incentives for farmers and land managers to adopt nature-positive practices. Greater public and private sector investment in research and innovation is needed, if we are to develop solutions and adequately scale the adoption of nature-positive production systems. Furthermore, a realignment towards nature-positive food systems requires awareness and empowerment on the part of producers and consumers. These concepts must be introduced to farmers through robust extension programs, with special attention paid to woman farmers. They must be taught in schools and broadcast to consumers. Ultimately, the aim should be to foster a five-way dialogue between academic institutions, farmer and citizen groups, industry and policy makers to translate scientific knowledge into viable action.

1. INTRODUCTION

This paper provides a high-level overview of evidence in favor of nature-positive food systems, discussing opportunities and challenges associated with sustainable, efficient agricultural production with a view to concrete policy suggestions. The aim is to present these complex issues comprehensibly and impartially, so that proposed actions are science-based, solution-oriented, applicable, and restorative, balancing trade-offs and optimizing available synergies.

2. WHAT DO WE WANT TO ACHIEVE?

The primary objective of the Food Systems Summit 2021 (FSS 2021) is to achieve multiple Sustainable Development Goals (SDGs) by internationally coordinated actions across the food system chain (production, distribution, and consumption). More concretely, the overall goal is to provide healthy and nutritious food to all people, while creating livelihood opportunities and reducing the negative environmental, climate, and health impacts associated with food systems. The Five Action Tracks of UNFSS-2021 will explore achievable means to: 1) ensure access to safe and nutritious food; 2) shift to sustainable consumption; 3) boost nature-positive production; 4) advance equitable livelihoods; and 5) build resilience to shocks and stress. Here, as a brief paper for the Action Track 3 of the Food Systems Summit 2021, the focus is on food production systems, primarily on land. Food systems in water, whether at sea or in aquaculture, are equally important, since fish and seafood help to assure healthy diets. This part of food systems is dealt with in a planned separate evidence-based Brief for the Scientific Group for the Food Systems Summit.[1]

Definition

Nature-positive food systems are characterized by a regenerative, non-depleting and non-destructive use of natural resources. It is based on stewardship of the environment and biodiversity as the foundation of critical ecosystem services, including carbon sequestration and soil, water, and climate regulation. Nature-positive food systems refer to the protection, sustainable management and restoration of a productive system. Finally, nature positive food systems cover the growing demand for food in a sufficient way and include sustainable and healthy nutrition.

1 Researchers who are part of the Blue Food Assessment (BFA; https://www.bluefood.earth/).

The current global food production system is the result of 100 years of successful scientific and technical innovation. Yields of agricultural crops have increased more than ever before in human history, with sharp increases in production efficiency per area and per labor unit. Resultantly, the 20th Century has seen an increase in the production of food greater than the growth of the global population. However, this development entails considerable trade-offs. It negatively impacts climate stability and ecosystem resilience. Scientific assessments by IPCC (2019) and IPBES (2019) have concluded that many aspects of current food production systems drive degradation of land productivity, water resources and soil health, as well as biodiversity loss at multiple spatial scales, ultimately compromising the sustainability of food production systems. The IPCC Special Report on Climate Change and Land (IPCC, 2019) has comprehensively laid-out the ways in which food systems, as they currently function, undermine our ability to feed the projected 10 billion global population by 2050. Another report, from IPBES (2019), shows that one million species are threatened with extinction, which impacts human well-being associated with biodiversity, indicating that agriculture, as a key driver of deforestation and the depletion of ocean resources, is responsible for a significant part of this biodiversity crisis. Similarly, the latest Living Planet Report (WWF 2020) revealed that the most important direct driver of biodiversity loss in terrestrial systems in the last several decades has been land use change – primarily the conversion of pristine native habitats (forests, grasslands and mangroves) into agricultural systems – while much of the oceans have been subject to overfishing. Meanwhile, in freshwater ecosystems, biodiversity loss as a result of food production has increased by 50%. Agriculture accounts for some 70 percent of freshwater withdrawals worldwide and contributes to water pollution from agrochemicals, organic matter, drug residues, sediments and saline drainage into water bodies (Mateo-Sagasta et al., 2018)

The degradation and fragmentation of natural and semi-natural ecosystems is known to increase the risk of emergence and spread of zoonotic diseases such as Ebola, HIV, SARS and COVID-19. Habitat loss of wild animals, overall loss of biodiversity, in addition to contact possibilities of wild animals with large livestock populations, are become greater, risks of zoonosis increases (Keesing and Ostfeld 2021). Humans depend on the stable and adaptive interaction between plants, microorganisms and life-support systems such as water and soil. Hence, we need a radical transformation of current food systems tending to disrupt these beneficial interactions. Such transformation must encompass all of relevant environmental and socio-economic elements: affecting the environment, people, inputs, processes, infrastructures, institutions and all activities that relate to the production, processing, distribution, preparation, consumption, and waste-disposal of food (see Action Track 1, Bortoletti & Lomax, 2019; HLPE, 2014).

The need for a comprehensive approach in nature-positive food systems is also recognized through the development and promotion of various interconnected and complementary elements such as the ten elements of agroecology (FAO 2018a):

- Diversification and resource use efficiency, including local varieties to protect food security; increasing productivity and improving nutritional balance through the consumption of diverse kind of cereals, pulses, fruits, vegetables and animal source proteins; intercropping and crop rotation practices for resource efficiency.
- Increased resource efficiency through innovative practices to produce more with less external resources and create synergies between the system components; recycling biomass, nutrients and water to reduce external resources; reducing costs and negative externalities.
- Fostering synergies and promoting multiple ecosystem services to increase resilience: e.g. biological nitrogen fixation in intercropping or rotations reduce the need of external fertilizer and contributes to soil health and climate change mitigation.
- Recycling of nutrients, biomass, and water: minimizing waste and pollution with lower economic and environmental costs.
- Improving resilience through crop-system diversification: maintaining a functional balance so that production systems can tolerate pests and diseases or reduce the magnitudes of pest outbreaks. With diversification, producers reduce their vulnerability because they will have several options in case any product fails.
- Promoting the acceptance and implementation of innovations through the promotion of participatory processes to share knowledge and co-create solutions to local challenges.
- Protecting human and social values and improving rural livelihoods, where dignity, equity, inclusion, and justice are an integral part of sustainable food systems, trade, and employment. Since culture and food traditions play a central role in society and in shaping human behavior, they are closely tied to landscapes and food system.

- Fostering responsible and effective governance at local, national and global levels, maintaining the transformation processes for sustainable FS. These include incentives for ecosystems services.
- Supporting innovation for circular and solidarity economies within the planetary boundaries and reconnecting producers and consumers as the basis for inclusive and sustainable development. Here, local markets and local economic development are key, while circular economies can help to tackle the global food waste challenge, making food value chains more resource efficient at every level.

The global community of policy makers as well as actors along the entire food chain, supported by citizens, must jointly transform the current "net-nature-negative" into "nature-positive" situations at the global scale, by developing and applying effective and efficient incentives. This means fostering and enhancing positive practices in existence, while reducing impacts from negative practices at the landscape level. Such practices are innovations in soil and water management, land use planning, biodiversity conservation, circular economy approaches, new science and technologies in molecular biology and plant breeding, alternative protein sources, and digital tools for the management of agriculture, and land and natural resources. In doing so, boosting nature-positive food systems will put the global society on a pathway to a more resilient future and sustainable well-being in line with the Building Back Better Initiative of the United Nations (Mannakkara et al., 2019). Food, feed and fiber production must support biodiversity, restore soils, protect freshwater supplies, increase water security, withdraw carbon from the atmosphere and store it in the terrestrial biosphere (i.e. soils, trees and wetlands), create employment, increase food security, and enhance climate resilience and social stability. In response to the Covid-19 pandemic, the necessity of changing the production systems more sustainable and circular is all the more urgent. Simultaneously, the current crisis provides a unique opportunity to challenge the perceived dilemma between economic growth and environmental stability.

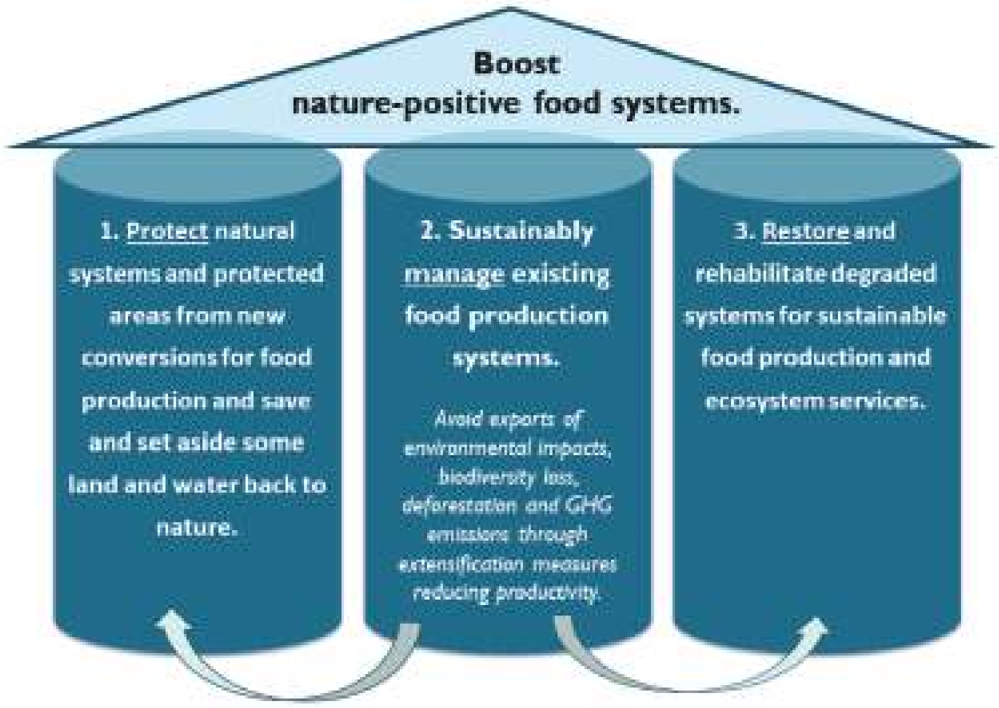
3. WHAT DO WE MEAN BY NATURE-POSITIVE FOOD SYSTEMS?

Nature-positive food systems globally meet the fundamental human right to healthy food, while operating within boundaries that limit the natural resources available for a sustainable exploitation (Steffen et al., 2015). Using the concept of a safe operating space for food systems, the EAT-Lancet Commission has prepared an outline of human health and environmental sustainability for global food systems with clear scientific targets (Willet et al., 2019). They described six central environmental dimensions for planetary health using the planetary boundaries concept for food production to ensure a stable Earth system (Table 1). These dimensions take into account the environmental limits within which food systems should jointly operate, ensuring that a broad set of universal human health and environmental sustainability goals are achieved (Willet et al., 2019).

Table 1 Scientific targets for six key Earth system processes and the control variables used to quantify the planetary boundaries. Source: Willet et al., 2019.

Earth system process	Control variable	Boundary (uncertainty range)
Climate change	Greenhouse gas (CH_4 and N_2O) emissions	5 Pg of carbon dioxide equivalent per year (4·7–5·4)
Nitrogen cycling	Nitrogen application	90 Tg of nitrogen per year (65–90;* 90–130†)
Phosphorus cycling	Phosphorus application	8 Tg of phosphorus per year (6–12;* 8–16†)
Freshwater use	Consumptive water use	2500 km³ per year (1,000–4,000)
Biodiversity loss	Extinction rate	Ten extinctions per million species-years (1–80)
Land-system cha	Cropland use	13 million km² (11–15)

Figure 1 The three pillars of nature-positive food systems



Cohen-Shacham et al. (2016) have defined the term Nature-based Solutions (NbS), an overall concept that we use for nature-positive food systems accordingly. It is based on three pillars: "protect", "sustainably manage" and "restore" (agro)ecosystems.

3.1 FIRST PILLAR: PROTECT NATURAL SYSTEMS AND PROTECTED AREAS FROM NEW CONVERSIONS FOR FOOD PRODUCTION AND SAVE AND SET ASIDE SOME LAND AND WATER BACK TO NATURE.

Any further conversion of natural ecosystems and undisturbed habitats should be halted. Land use change, especially the loss of forests and trees in the landscape through farming and the expansion of intensive agriculture and large livestock populations, are critical drivers of risks related to the exposure to emerging infectious diseases (Shaw et al., 2020) and destabilize the safe operating space of humanity (Steffen et al., 2015). Exploiting natural land for agriculture can lead to drastically increased emissions of greenhouse gases (GHGs) and losses of biodiversity (Kiew et al., 2020; Dargie et al., 2017). Important drivers are high-income countries, which import large amounts of food and feed from unsustainable farming systems in low- and middle-income countries. As this generates a significant incentive for such unsustainable activities, importing countries should also take responsibility for protecting lands elsewhere – in a globalized world, these also constitute part of their food system.

Likewise, agriculturally marginal lands that are areas of high biodiversity (e.g. steep lands, shallow soils, wetlands, peatland) must be protected. As poverty and lack of knowledge are significant drivers of habitat destruction, protection of such natural systems requires actions that change radically societies and economies. Many smallholder farmers are locked into low yields and highly degrading livestock practices (Garrett et al., 2017). These practices persist because of historical legacies, political instability, market failures, cultural lock-in and fire risks. However, very importantly, the preservation of natural ecosystems depends on how successfully humanity can manage existing production systems in a productive and sustainable way. The three pillars interact directly and indirectly, sometimes with actions in one place with intended and unintended consequences in remote places (Garrett and Rueda 2019, Eaking et al., 2014): getting more food from less land (see pillar 2) enables restoring degraded farmland (see pillar 3), and safeguarding natural ecosystems and returning some land back to nature (pillar 1). Setting aside land and water is made possible by more efficient production on existing agricultural land. Extensification measures compromising yield on productive land export negative externalities by importing food.

3.2 SECOND PILLAR: SUSTAINABLY MANAGE EXISTING FOOD PRODUCTION SYSTEMS

Nature-positive food systems characterized by a regenerative, non-depleting, and non-destructive use of natural resources (Lal, 2020). It is based on biodiversity as the foundation of ecosystem services – particularly soil, water, and climate regulation – that farmers manipulate with external inputs and with human or mechanical forces. For terrestrial food production, healthy soil and clean water are the essential means by which we produce healthy food (Lal, 2017). Equally essential are pollinators, on which 70 % of the crops depend (Reilly et al. 2020). These will be the most critical indicators of success in producing nature-positive outcomes. Here, as always, the need is to work towards food systems that deliver net-positive ecosystem benefits.

Nature-positive production hinges upon circular bioeconomy, in which local and regional integration of production, consumption and the use of all residues are integrated and balanced. It aims for strong innovation, but balances different types of innovation – the social, environmental and technological – in an equal manner. Production systems are driven by the pure food needs of a growing population, which means that society needs to focus on sustainable dietary patterns (reduced food waste and reduced reliance on cereal-based meat and dairy products) and reduced production of energy crops on arable land. As a consequence, the efficiency narrative ("produce more from less") must be complemented by the sufficiency narrative ("consume moderately") to avoid rebound effects (Müller & Huppenbauer, 2016). The nature-positive food system recognizes the fact that health of soil, plants, animals, people, ecosystems, and, ultimately, the planet is one and undividable (Lal, 2020). A transformation of agriculture towards nature-positive food systems depends, first of all, on actions at the **landscape** scale, as defined by the Organization for Economic Co-operation and Development (OECD 2001, 2007). Here, ethical and political framing of issues, financial and infrastructural incentives, and the general innovation strategies and the degree of participation of stakeholders and actors are designed and decided upon. Dietary behavior of the population at large, and the way food is handled, is also an issue that shapes the landscape. The second level is the **management practice** and **production technology** of the entire value chain that must be linked to the objectives of improving and maintaining non-commodity ecosystems services in productive agriculture. In nature-positive production systems, the technologies used are consistent with the salient and contextual territorial, cultural and socio-economic conditions, and are compatible with natural processes. Currently, a significant share of food production fails to meet these criteria. Nonetheless, some farming systems and technologies already perform better in this respect than others. These approaches include agroecological practices, regenerative conservation agriculture, integrated nutrient and pest management, river basin management, sustainable groundwater management, agroforestry and agro-silvo-pastoral systems and sustainable pastoralism in the rangelands. The development and use of bio-inputs such as bio-fertilizers and bio-protectants is another environmentally-friendly approach, combined with integrated crop management, intercropping and cover cropping. Some strategies include precision agriculture and climate-smart agriculture. Several specific programs for farmers target individual improvements, such as introducing semi-natural habitats on the farm, applying no-till arable cropping, or strictly reducing the use of pesticides and nitrogen fertilizers.

Many examples of traditional food production systems involving landscape-level management exist. Many rural settlements in Asia and Africa have sustained their productive landscapes for centuries: for example, "satoyama" in Japan (Kobori & Primack 2003; JSSA 2010; Indrawan et al. 2014). Likewise, sustainable socio-ecological landscapes involving a variety of traditional approaches have been continuously fine-tuned by people in response to the climate and soil characteristics of their lands. These provide hints for low-cost and sustainable watershed management, which could be scaled up with modern technologies involving optimal and sustainable land use design.

3.3 THIRD PILLAR: RESTORE AND REHABILITATE DEGRADED SYSTEMS FOR SUSTAINABLE FOOD PRODUCTION AND ECOSYSTEM SERVICES

One-third of global land area is degraded (FAO, 2015b), comprising of 47% of forest and 18% of cropland (Bai et al. 2008). There are approximately 2 billion hectares of degraded and degrading lands in the world. Resultantly, the potential for restoration or rehabilitation is huge, and as such it is key to avoiding new conversion of natural habitats and ecosystems. Here, specific technical measures must be taken depending on the site, socio-economic and cultural conditions.

One option is targeted at rewilding natural ecosystems at the landscape level to restore soil health, enhance biodiversity, and ecosystem services. Such activities often have additional benefits, as they could increase resilience. Another option involves rehabilitating of agricultural productivity, and this is equally important. Both of these forms of land restoration can help sequester carbon (IPCC 2019). In this context ideal results typically occur when scientific information and traditional, local knowledge cooperates in finding solutions. The potential offered by such partnerships in helping to avoid new conversion of natural habitats and ecosystems and in reverting some agriculturally marginal land back to nature is enormous (Lal, 2021). Specific measures must be taken depending on the local bio-physical, socio-economic and cultural conditions (including pillar 1 measures). In addition, intensive cooperation and benefit sharing with all actors and stakeholders involved in a region or site must be ensured. The development and use of adequate financial mechanisms and public policies must be based on their social, environmental and economic returns. And research must focus on new knowledge and technologies to restore land and soils, in collaboration with food producers and other actors in the landscape.

4. CHALLENGES OF NATURE-POSITIVE FOOD SYSTEMS

The transition to nature-positive food systems is slowed or made impossible by numerous agronomic, economic and social challenges, which are compounded by deficits in knowledge systems.

4.1 AGRONOMIC CHALLENGES

Yield reductions related with nature-positive production

Replacing conventional systems or subsistence farming in marginalized conditions with diversified nature-positive production can increase the overall output of farms (Pretty et al. 2018). However, on average, and particularly in temperate zones with highly intensive agriculture, conversion to nature-positive systems typically results in a reduction of yields that must be compensated by cost savings, higher product prices, or other support measures, as to ensure the economic viability of the farms. This is particularly true in the case of organic farming (Knapp & van der Heijden 2018; Seufert et al. 2012), but much less distinctive for integrated production systems with restrictions on plant protection and nitrogen fertilization (Morris and Winter 1999). The trade-off between high yields and biodiversity-rich, non-commodity ecosystems services such as soil nutrient cycling, soil carbon sequestration, pollination and indirect pest control, is the greatest challenge of the present.

4.2 ECONOMIC CHALLENGES

Higher labor demand

Nature-positive food systems have a high initial demand for labor and can be more labor-intensive in general. This can be a serious constraint when manual labor cannot be substituted by mechanized labor. In situations where mechanization is possible, the investment required can also be a hurdle. However, provided that work conditions are decent, this can also be an opportunity for job creation.

Higher transaction costs

As nature-positive food systems are more diverse, they tend to yield a greater number of crop or livestock products with a smaller volume of each product. This can limit market and processing opportunities and requires high levels of knowledge and risk taking/experimentation. Furthermore, farmers may have to carry the financial and knowledge burden of identifying and applying alternative inputs. A number of nature-positive practices depend on collective action across a landscape scale, involving multiple farms and a range of actors. This requires higher levels of coordination and increases transaction costs.

Failed valorization of sustainability throughout the value chain

Healthy, safe and sustainably produced raw materials and food are desired by policy makers and citizens worldwide. However, these additional services are not rewarded in the value chain, neither at the farm level, nor at the level of processing, trade and consumption. Cheap food continues to be purchased predominantly because consumers have other priorities in their household budgets or because they cannot afford it.

A major challenge is that monocropping of calory-dense food commodities offers large scale-economies and lower unit costs, as opposed to the more diversified production of a portfolio of food commodities needed for a healthy diet.

4.3 POLITICAL CHALLENGES

Policy incoherence

Current agricultural and trade policies, including subsidy schemes, still favor intensive, export oriented production of a few crops and there are still incentives for the use of fossil fuel and chemical inputs in place (Eyhorn et al., 2019). Furthermore different governmental policies are contradicting and conflicting, especially agriculture, environmental, health, trade and science/education policies. Finally, the transition towards nature-positive farming is decelerated by past decisions of farmers such as the investment in large machines, skills, and retail relationships (HLPE 2019, IPES-Food 2016). A return on those investments is more difficult when farmers shift their strategy towards nature-positive food systems. Therefore, reorientations of governments towards more ecological and social sustainable goals are always retarded.

4.4 DEFICITS ALONG THE AGRICULTURAL KNOWLEDGE SYSTEMS

Weak knowledge and advisory systems

Public and private investment in research on nature-positive food systems has been substantially lower in comparison to other innovative approaches, which results in significant and persistent knowledge gaps (HLPE, 2019). A systems-oriented, transdisciplinary, and long-term field research approach is clearly lacking (Edwards & Roy 2017). Therefore, there is a disconnect in the knowledge and advisory systems required to support nature-positive food systems and build the capacity of actors.

There is also a shortage of inter- and transdisciplinary research on nature-positive food systems that takes into account the context specificity of the approaches. Nature-positive system thinking and solutions are not sufficiently well integrated into the curricula of universities and farmer schools.

5. CALL FOR ACTIONS TO SUCCESSFULLY COPE WITH TRADE-OFFS AND SCALING UP NATURE-POSITIVE FOOD SYSTEMS

There are several structural lock-ins that keep the current unsustainable food production system in place. These create a set of feedback loops that reinforce this system and include investments and policies that create path dependency, such as purchasing of expensive equipment or subsidies for chemical pesticides, export orientation, the expectation of cheap food, compartmentalized and sectoral, shortterm thinking, certain discourses about feeding the world and focused solely on production volumes and measures of success (looking at single crops) (IPES-Food 2016). Other typical lock-ins that reinforce the current system are the concentration of power in the food chain and institutional, agricultural research and technological lock-ins (WWF, 2016). Therefore, a systematic change towards nature-positive food systems requires a fundamental reorientation of many societal actors and a realignment of the cooperation between them. The inclusion of local actors, particularly of the most vulnerable voices, in decision-making will lead to more effective solutions. The nine actions can provide guidance to ensure an integrated, systemic approach.

Action 1: Increase policy coherence and strengthen adequate governance

Nature-positive food systems require a different type of government support that goes beyond incentives such as income-oriented subsidies or those for particular inputs or unspecific marketing actions. Further research is therefore needed to better understand which government policies can support nature-positive food systems and multi-functionality of agriculture more generally. Importantly, more information is needed on the public and private costs of sectoral approaches that result in contradicting and conflicting policies.

The decisive level in fostering transition is the landscape. This is the level where actors and innovations come together and where food producers' strategies interact with other users of the landscape, with governance policies and with natural systems. Sustainability at the landscape level is essential for water and soil management. The health of upland watersheds, for example, can be critical to water regulation and recharge, and the stabilization of soils. For this reason, the landscape approach has been promoted by agencies such as the Organization for Economic Co-operation and Development (OECD 2001, 2007) and the European Union (European Commission, 2006) as the scale at which it is most meaningful to align polices and incentives towards nature-positive outcomes. Landscape-level regulations and incentives, as well as infrastructure planning and other intervention strategies should be designed and decided at this level, preferably through inclusive, participatory processes and institutions. An important element in these interventions is therefore not just the creation and sharing of knowledge, technologies and practices that better link to the objectives of improving and maintaining non-commodity ecosystems services, but importantly the governance systems that are driving certain technologies, processes or behaviors.

Landscape-level governance is critical. Governance frameworks – including, for example, regulations, incentives and extension programs – influence farmers everywhere and play a crucial role in the adoption of good farming practices. In some countries, these governance systems are quite sophisticated cascading systems that are clearly targeted to promote sustainability. Laws and regulations on environmental, human and animal health, animal welfare or land management are effectively implemented so that farmers who are found to be in violation can be fined or excluded from related government support and services. Farmers receiving income support have to respect additional environmental standards such as maintaining soil quality or protecting groundwater, landscape and biodiversity (cross-compliance). A powerful incentive for the adoption of sustainable agricultural practices and especially nature-positive production are payments for ecosystem services (Piñeiro et al., 2020).

However, in other countries, governance institutions may not administratively align with landscape levels or may not be adequately empowered or well-resourced to implement similar efforts. In these cases, in parallel to broader governance strengthening, nature-positive practices can be more immediately advanced through mechanisms including support for relevant applied research and extension activities, land conservation and restoration efforts, education and training, facilitation of access to credit and insurance, and legal and administrative reforms to secure land tenure and enhance farmers' willingness to invest in sustainability.

Unfortunately, the transition towards nature-positive farming can be decelerated by incentives for food producers to invest in large machines, skills, and retail relationships that are economically attractive only if applied in unsustainable farming systems (HLPE 2019, IPES-Food 2016). Similarly, large subsidies on agricultural water promote unsustainable water usage while subsidies on pesticides and fertilizers can encourage overuse resulting in degraded water quality. These lock-ins make it difficult for producers to shift their strategy towards more nature-positive food systems.

Additional to the efforts and advances of several agencies connected with UN and CGIARs, it is essential to coordinate and integrate several relevant initiatives ongoing globally such as Water, Land and Ecosystems (https://wle.cgiar.org), EarthBioGenome (https://www.earthbiogenome.org), Future Food Systems, Australia (https://www.futurefoodsystems.com.au), Next Generation Food Systems (https:// www.ucdavis.edu/news), DivSeek International Network (https://divseekintl.org), CropBooster-P (https://www.cropbooster-p.eu), EMPHASIS –ESFRI- (https://emphasis.plant-phenotyping.eu), and Living Soils of the Americas initiative (https://iica.int), among others.

Action 2: Improve sustainable soil management

Soil degradation, being exacerbated by the climate change along with land misuse and soil mismanagement, is worsening the malnutrition already affecting more than 2 billion people globally (Lal, 2009). Restoration and sustainable management of soil are also critical to enhancing and maintaining ecosystem services, identifying and implementing nature-positive agriculture, producing more food from less land, and advancing the UN SDGs (e.g. SDG#2, Zero Hunger, SDG #13, Climate Action, SDG #15, Life on Land) (Lal et al., 2018). Developing resilient food production systems for local consumers is especially important during the COVID19 Pandemic which promotes food production by urban agriculture and home gardening (Lal, 2020). Achieving the targets of land degradation neutrality, adopted by the United Nations Convention to Combat Desertification, will also improve nutritional quality of the food. Translating into action the concept "health of soil, plants, animals, people and environment is one and indivisible" by restoration of degraded soils and adoption of nutrition-sensitive agriculture will also improve human health and well-being (Lal, 2020). Soil health and its capacity to generate ecosystem services must be enhanced through sequestration of soil organic matter content by adopting a system-based conservation agriculture, enriching the soil by planting nitrogen-fixating plants or adding N fixating microorganisms, mycorrhizae, growing cover and inter-crops, diversified crop sequences, and integrating crops with trees and livestock in agro-silvopastoral systems (Jensen et al., 2020; Smith et al., 2012). Adoption of nature-positive practices that enhance soil organic matter content can reduce dependence on chemicals, irrigation, tillage and other energy-intensive inputs, and would reduce losses of nutrients and water, enhance eco-efficiency and sustain productivity. Sequestration of soil organic carbon has been recommended by several international initiatives such as 4p1000 adopted by COP21 in Paris in 2015, Adapting African Agriculture by COP22 in Marrakech in 2016 (Lal, 2019), Platform on Climate Action in Agriculture by COP25 in Madrid/Santiago and the international initiative for the Conservation and Sustainable Use of Soil Biodiversity under the Convention on Biological Diversity.

Nature-positive production implies adaptation to climate change, protection and enhancement of soil health and food security. This can be achieved through bioeconomy strategies with the approach of integrated cycles in whole value chains to increase efficiencies by recycling resources through diverse products and coproducts in animal, plant, and microbial systems. The goal is to promote resource efficiency while enhancing productivity, and increase resilience in crop systems able to cope with biotic and abiotic stresses.

Action 3: Boost knowledge and innovation for nature-positive food systems

The dramatic increase in food demand projected for 2050 requires a broad-based environmental, social and technological innovation strategy; one that is supported by farmers, scientists, food value chain actors and citizens. Innovations must not be hindered if they serve the goals of nature-positive food systems.

Ecological innovations or optimizations are driven by biodiversity and ecosystem functions. Most fundamentally, soil fertility is vital to plant growth factors, such as mineralization of nutrient elements, water supply, aeration and loosening of the root zone and rooting depth. **Social innovation**s include those in the socio-economic space, such as new ideas for the governance of landscape-level networks, innovation of institutions, novel approaches to building farmers organizations, creative use of finance to support these transitions, co-operations in marketing and food distribution such as Community Supported Agriculture (CSA), as well as new modes of learning and capacity building. **Technological innovations** encompass digitalization, the smart use of data for prediction and prevention, various breeding techniques, production of bio-inputs or the separation, processing and recycling of organic waste.

Innovations across all of these categories can be mutually reinforcing, particularly when they are embedded in the systems approach of nature-positive food systems. Therefore, strict criteria for the choice of technological innovation must be applied consistent with this paradigm. Centrally, these include requirements for the protection of biodiversity, reduction of greenhouse gas emissions, improvement of biological and physical soil quality, human well-being, equitable access regardless of farm size and gender, and compatibility with traditional knowledge. In light of this, technological innovations must always be sensitively integrated with local cultural and affiliated knowledge contexts, under the aegis of an overarching systems approach.

Already, global agriculture is undergoing major transformations through this kind of technology convergence, such as new digital technologies and the use of artificial intelligence to optimize agricultural production processes. Drones and advanced analysis of image data can identify pests and diseases in real time and provide a powerful toolbox for all farmers regardless of farm size. With improved access to biotic (pests and diseases) or physical (meteorological, Sistema de Alerta Temprana (SAT) or early warning systems) information and remote sensing, producers can use their mobile phones to strengthen their practices, making the best use of resources and inputs. Digitalization has been developed on and for broad-acre farms. The technology can work flexibly and on a small scale. It can intervene with pinpoint accuracy and the devices become smaller, lighter and work in coordinated networks. The software makes it possible to carry out operations in small spatial and temporal structures in an efficient, labor-saving and energy-saving way. Depending on how the algorithms are programmed, networking and diversity emerge. Further developments also promise to make such technologies affordable for small and medium-sized farmers.

Parallel to digital technologies, novel bio-inputs provide a valuable supplement to NbS (Syed Ab Rahman et al., 2018; Liu et al. 2018; Kavino & Manoranjitham, 2017). It is crucial to promote and strengthen studies in plant microbiome which comprises all micro- and macro-organisms living in, on, or around the plant, including bacteria, archaea, fungi, and protists for food security (d'Hondt et al., 2021). We recommend that greater emphasis be given to the development of green technologies that deploy indigenous perennial species, tapping into the symbiotic relationships that naturally exist between microbes and plant species (Hohmann et al., 2020). In the African context, for example, it has already been established that the combined use of many different beneficial microorganisms (producing multi-strain or multi-bacterial inoculants) can greatly boost nature-positive production (Adedeji et al., 2020).

A similar role can be played by bio-stimulants from land and marine/ocean resources (e.g. Kelpak from seaweeds, molecules such as lumichrome, riboflavin, and nodulation factors from soil rhizobia and other mutualistic microbes), which replace chemical fertilizers in promoting crop plant growth and increasing yields. Plant protectants, such as botanicals (plant extracts) are currently under-exploited, but we can look to future scientific and technological developments to increase the portfolio of bioproducts developed from the local biodiversity, in keeping with a circular economy approach.

Maintaining and increasing biodiversity in agricultural settings is key to fostering and expanding nature-positive food systems, and can yield additional benefits for consumers. For example, local cultivars that are often more nutritious than common staples and better adapted to local climate and soil conditions (Leclère et al., 2020). Subjecting these to conventional and molecular breeding programs, including gene editing, capitalizes on their inherent advantages, improving productivity and/or tolerance to adverse biotic or abiotic conditions. In the context of climate change, these methods may be critical for maintaining beneficial agrobiodiversity in the face of new environmental pressures. This underlines the need for advanced knowledge in plant genetic diversity, microbial diversity and interactions, taking into account local climate variability, soils, nutrients, water and contextual environmental impacts.

To conclude, the key to successful innovation in support of nature-positive food systems lies in developing these technologies with the active participation of farmers, consumers, and citizens. This ensures that measures adopted locally are the most suited to their specific conditions and cultures. In the future, the target system, which we have defined as nature-positive, will guide the development of technologies and their use, and not vice versa. At the same time, interdisciplinary approaches are required to make the best use of advances in molecular, sensor, and modeling sciences, which can be used to understand and predict production patterns. The use of multiple phytobiomes will be needed along with integration of molecular, ecological, and evolutionary information to obtain significant models. The outcome of this transformation in research practices should be made accessible to food producers on the ground, building on knowledge and resources that are already locally available. In this way, international and collaborative research and local, contextual knowledge systems are harnessed together in support of the overarching aim to save costs and reduce environmental impact: producing more food and fewer negative externalities (WRI, 2018).

Action 4: Adapt and intensify the knowledge sharing of farmers, farm advisors and farm teachers.

As immediate actions, the better understanding of nature-positive production within its complexity can be considerably improved. The scientific knowledge is tremendous, but its integration with the knowledge of farmers, consumers and citizen remains vastly unsatisfactory. The promise of traditional knowledge practiced by indigenous peoples and local communities is still underestimated compared to modern scientific knowledge. This in part reflects the fact that the former remains critically under-documented. In order to stimulate interactions between traditional knowledge and science-driven innovation, greater cooperative work in the context of local farms, including the joint design of experiments, are an effective approach. To interest farmers in long-term solutions, the time lag between action and results and the risk related to it, could be compensated with financial support during the first few years of transition. For farmers, co-learning activities that prominently include farmers and consumers, are important. Scientists and farm advisors should learn to use the power of peer-to-peer learning and collaborative action among and with farmers. These are attractive, fruitful, and satisfying alternatives to providing top-down advice. Here, a complete overhaul of agricultural extension services in terms of capacity issues, incentives and accountability to farmers will accelerate transition. Additionally, innovative approaches, like using vouchers for advisory services should be promoted. These can be given directly to farmer group associations to source extension services from private providers. A combination of public funding and private delivery, based on the farmers satisfaction with services provided and the pro- motion of nature-positive food systems, can be combined with entrepreneurial proficiency. Likewise, ICT use for information and advisory services, in partnership with private providers, should be scaled up.

In light of these proposals, a real revival of agricultural education at universities and farm schools is needed. The complex interdisciplinary concept of nature-positive food systems has to become gradable content in teaching, adaptive experimentation, and locally relevant information exchange. So reformed, the mutual permeability of educational institutions would promote understanding for the transformation of agriculture and its actors. Most of all, public investment in research on nature-positive production should be considerably increased. As nature-positive production requires complex decisions, coping with uncertainties and trade-offs, as well as taking higher risks of failures, inter- and transdisciplinary research is a prerequisite.

Action 5: Strengthen information for citizen on sustainable nutrition and food diets.

The development and scaling-up of nature-positive production is dependent on the transition to sustainable consumption and more plant-based diets. In many countries, market forces determine access to healthy, sustainable and nutritious food (Action Track 1). One aspect of sustainable nutrition means a higher degree of sufficiency or consumer moderation, characterized by a reduction of food wastage. Food wastage varies in considerably across different contexts and is influenced by socio-economic and cultural factors. In addition, a significant part of the unavoidable food losses should be reused via a circular economy of feed and food. Furthermore, competition for the scarce resources of arable land and water between food, feed and energy production must be reduced. Global food mass flow models show that by using arable land primarily for direct human nutrition while maintaining grassland-based dairy and meat production with ruminants, the goals of preserving biodiversity and environmental integrity and securing human energy and protein supply by 2050 could be achieved together (Schader et al., 2015, Müller et al., 2017). Such changes in human nutrition and eating habits influence and change land use, ultimately reversing the loss of biodiversity (Leclerc et al., 2020), decreasing GHG emissions (Bajželj et al., 2014; Tilmann & Clark, 2014) and improving the ecological footprint (Westhoek et al., 2014).

How can arable land be primarily used for human nutrition? Energy production on arable land can be reduced by ending state subsidies for the cultivation of these crops and for the production of biogas. Here, more energy-efficient and economically-viable alternatives to fossil fuel already exist in the form of solar and wind energy (Blankenship et al., 2011). The collective change of individual consumption and eating patterns presents a more difficult challenge. In the first place, it requires better information, dissemination and integration of sustainable nutrition into the curriculum of schools. Therefore, it will be a multi-generation effort. Further activities can include the development of personalized shopping guidance and all kind of nudging campaigns. Furthermore, levies and taxes on the transport of concentrated feeds or on the consumption of meat could lead to behavioral changes and make plant proteins more attractive. Meat substitutes based on plant components or on animal cells grown in the laboratory are already technically possible, but currently remain prohibitively expensive (Furuhashi et al., 2021). However, less drastic solutions are still open for exploration and adoption. For example, replacing plant protein in animal feed with insects grown on organic waste materials can also be much more climate-friendly than conventional methods van Huis et al., 2013). More ambitiously, raw materials for processed foods that are still underused, such as algae, would be almost inexhaustible and ecologically less burdensome for human nutrition (Ścieszka & Klewicka, 2019).

Action 6: Empower rural areas by cross-farm co-operations and through high local value creation

Any activities that strengthen rural societies, including through local and regional markets, Participatory Guarantee Systems (PGS), certification systems for remote markets such as Voluntary Sustainability Standards (VSS), or organic farming, can considerably improve farm incomes and livelihoods. There are many successful examples of how this kind of social innovation help boost nature-positive production. To strengthen territorial development, the value addition to products must take place at the local and regional levels, and so related regional networks must be strengthened.

Nature-positive farming systems usually give rise to a larger number of farm activities and more products that need to be marketed. This is especially true for agroforestry systems, for example, where several layers of food crops and energy plants are grown (Ajayi et al., 2009). Currently, there is a lack of adequate market and processing facilities for smaller volumes, which sometimes also require high levels of knowledge and experimentation. Greater emphasis should therefore be placed on supporting local processing facilities, as well as investment in local training in technologically simpler food processing, quality assurance, and, ultimately, improvement in storage and transport routes.

Nature-positive production systems have a high initial demand for labor and can be more labor-intensive in general, especially for women. This can be a serious constraint when manual labor entails onerous and low-skill work that cannot easily be substituted by mechanized labor. However, at the same time, it offers opportunities for employment, and to revitalize rural areas, particularly when labor conditions are decent and financial incentives are re-shaped (Schuh et al., 2019). Cooperative models of productive relations must therefore be supported so as to mitigate increases in workload.

Action 7: Improve access to land, water and biodiversity especially for women

Inadequate and insecure access and tenure rights for various elements of natural ecosystems (unfortunately a reality in the global North as well as the South) increase vulnerability and undermine nature-positive production. Insecure access provides little incentive for food producers to invest in long-term nature-positive production. Land fragmentation, soil degradation, climate change, large scale water and land acquisition all block the possibilities for nature-positive production, thus increasing the likelihood of environmental degradation.

Women are actively involved in food systems in several fundamental functions, growing and managing crops, livestock, agribusinesses and food retailing and additionally, in preparing food for their families. Women and women´s groups have been shown to be a critical partner in water and soil sustainable management. However, very often, they face restrictions that prevent them from participating on equitable and fair terms. The role of women in the transition towards sustainable food systems centrally includes increasing efficiency, changing diets, and improving integrated value chains. Inclusion means not only ensuring their participation and access to benefits, but more importantly guaranteeing their empowerment to make strategic life choices (Malapit et al., 2020). Thus, supporting sustainable and efficient food systems requires technologies, practices and policies that ensure women's participation and enhance their resilience.

6. CONCLUSIONS

The Calls to Action in this paper provide an integrated, systemic approach to realigning our food systems for a sustainable, resilient, 'nature-positive' future.

While today's food systems are "net nature-negative", they can and must become "nature-positive." Food systems across the world are driving habitat and biodiversity loss, land and water degradation, and greenhouse gas emissions. These phenomena, in turn, undermine the productivity, sustainability and resilience of food systems. This vicious circle can be broken if we take several fundamental steps to realign our food, feed and fiber production to achieve nature-positive agricultural production at scale. We must strive to: (i) protect natural ecosystems from degradation and conversion, (ii) manage existing production systems more sustainably in support of ecosystem health, and landscape-level resilience, and (iii) restore degraded ecosystems.

This realignment builds on innovations at the landscape level, including soil and water management, land use planning, biodiversity conservation, principles of agroecology and circular economy approaches, new science and technologies in molecular biology and plant breeding, alternative protein sources, and digital tools for the management of agriculture, and land and natural resources.

Importantly, shifting food systems from net nature-negative to nature-positive will require not only innovation in technologies and practices, but changes in food systems governance. This entails radical change in policies, investments, incentives, and subsidies that today fail to promote these practices. Nature-positive approaches will need to be integrated into agricultural extension programs, school and college curricula, and vocational educational programs. And they will need to build on broad, inclusive and empowered partnerships – with women, small-farmers, and the private sector among others – to co-create, promote, and entrench nature-positive innovation.

LITERATURE CITED

1. Adedeji AA, Häggblom MM, Babalola OO (2020) Sustainable agriculture in Africa: Plant growth-promoting rhizobacteria (PGPR) to the rescue. Scientific African Volume 9, https://www.sciencedirect.com/science/article/pii/ S2468227620302301
2. Ajayi OC, Akinnifesi FK, Sileshi G, and Kanjipite W (2009) Labour inputs and financial profitability of conventional and agroforestry-based soil fertility management practices in Zambia. Agrekon, Vol 48, No 3. https://www. econbiz.de/Record/labour-inputs-and-financial-profitability-of-conventional-and-agroforestry-based-soil-fer- tility-management-practices-in-zambia-ajayi-olu-clifford/10009446486
3. Bai, Z.G., D.L.Dent, L.Olsson and M.E.Schaepman (2008). Proxy global assessment of land degradation.Soil Use and Management 24(3);223-234.
4. Bajželj B, Richards K, Allwood J et al. (2014) Importance of food-demand management for climate mitigation.
5. Nature Clim Change 4, 924–929. https://doi.org/10.1038/nclimate2353
6. Benavides, R., Douglas, G.B., and Osoro, K. 2009. Silvopastoralism in New Zealand: Review of effects of evergreen and deciduous trees on pasture dynamics. Agroforestry Systems 76:327–350.
7. Blankenship RE, Tiede DM, Barber J et al. (2011) Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement. Science Vol 332, Issue 6031, pp 805-809.
8. Bortoletti M and J Lomax (2019). Collaborative Framework for Food Systems Transformation. A multi-stakeholder pathway for sustainable food systems. UN environment. ISBN: 978-92-807-37-3753-0. 58 pages.
9. Bowerman, P. (1993) 'Sequels to the Boxworth Project - studies of environmental, agronomic and economic effects of reduced crop inputs'. In: Journal of the Royal Agricultural Society of England 54: 45-59.
10. Braungart, M., McDonough, W. & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emission- a strategy for eco-effective product and system design. Journal of Cleaner Production, 15, 1337-1348.
11. D'Hondt K, Kostic T, McDowell R et al. (2021) Microbiome innovations for a sustainable future. Nat Microbiol 6, 138–142. https://www.nature.com/articles/s41564-020-00857-w.
12. Dargie, G., Lewis, S., Lawson, I. et al. K (2017). Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86-90. https://doi.org/10.1038/nature21048

13. Del Barrio-Duque A, Samad A, Nybroe O, Antonielli L, Sessitsch A and Compant S (2020) Interaction between endophytic Proteobacteria strains and Serendipita indica enhances biocontrol activity against fungal pathogens. Plant and Soil volume 451, pages 277–305.
14. Edwards MA & Roy S. (2017). Academic research in the 21st century: maintaining scientific integrity in a climate of perverse incentives and hypercompetition. Environmental Engineering Science 34: 51-61.
15. Eyhorn F, Müller A, Reganold JP, Frison E, Herren HR, Luttikholt L, Mueller A, Sanders J, El-Hage Scialabba N, Seufert V. and Smith P. (2019). Sustainability in global agriculture driven by organic farming. Nature Sustainability. VOL 2, 253–255.
16. FAO (2015a). Global guidelines for the restoration of degraded forests and landscapes in drylands: building resilience and benefiting livelihoods, by Berrahmouni N, Regato P and Parfondry M. Forestry Paper No. 175. Rome, Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/3/a-i5036e.pdf.
17. FAO (2015b). Status of World Soil Resources (SWSR). Food and Agriculture Organization of the United Nations and Inter-Government Technical Panel on Soils, Rome, Italy Available at: http://www.fao.org/3/a-i5199e.pdf.
18. FAO (2018a). The 10 elements of agroecology guiding the transition to sustainable food and agricultural systems. Available at: http://www.fao.org/3/i9037en/I9037EN.pdf.
19. FAO (2018b). Transforming food and agriculture to achieve the SDGs: 20 interconnected actions to guide decision-makers. Available at: http://www.fao.org/3/I9900EN/i9900en.pdf.
20. Furuhashi, M., Morimoto, Y., Shima, A. et al. (2021) Formation of contractile 3D bovine muscle tissue for construction of millimetre-thick cultured steak. npj Sci Food 5, 6. https://doi.org/10.1038/s41538-021-00090-7.
21. Garrett RD, Niles MT, Gil JDB, Gaudin A, Chaplin-Kramer R, Assmann A, Assmann TS, Brewer Ke, de Faccio Carvalhom PC, Cortner O, Dynes R, Garbach K, Kebreab E, Mueller N, Peterson C, Reis JC, Snow V and Valentim J (2017) Social and ecological analysis of commercial integrated crop livestock systems: Current knowledge and remaining uncertainty, Agricultural Systems 155 (2017) 136–146
22. HLPE. (2014). Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2014. http://www. fao.org/3/a-i3901e.pdf.
23. HLPE. (2019). Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.
24. Hohmann P, Schlaeppi K and Sessitsch A (2020) miCROPe 2019 – emerging research priorities towards microbe-assisted crop production. FEMS Microbiology Ecology, 96. https://doi.org/10.1093/femsec/fiaa177.
25. Indrawn M, Yabe M, Momura H and Harrison R (2014) Deconstructing satoyama – the socio-ecological landscape in Japan. Ecological Engineering 64: 77-84
26. IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K.
27. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zeno- do.3553579.
28. IPCC (2019): Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)].
29. IPES-Food (2016). From Uniformity to Diversity, http://www.ipes-food.org/_img/upload/files/UniformityToDiver- sity_FULL.pdf.
30. Jensen ES, Carlsson G and Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. Agronomy for Sustainable Development volume 40, Article number: 5, Springer Link. Available at: https://link.spring- er.com/article/10.1007/s13593-020-0607-x.
31. Jordan, V.W.L. and Hutcheon, J.A. (1994) 'Economic viability of less-intensive farming systems designed to meet current and future policy requirements: 5-year summary of the LIFE project'. In: Aspects of Applied Biology 40, pp 61-67.

32. Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: An overview. Agroforestry Systems 76:1–10.
33. Kavino M, and Manoranjitham SK (2017) In vitro bacterization of banana (Musa spp.) with native endophytic and rhizospheric bacterial isolates: novel ways to combat Fusarium wilt. Eur. J. Plant Pathol. 151, 371–387. doi: 10.1007/s10658-017-1379-2
34. Keesing F, & Ostfeld RS (2021). Impacts of biodiversity and biodiversity loss on zoonotic diseases. Proceedings of the National Academy of Sciences, 118 (17)
35. Kiew F, Hirata R, Hirano T, Xhuan W G, Aries E B, Kemudang K, Wenceslaus J, San LK and Melling L (2020). Carbon dioxide balance of an oil palm plantation established on tropical peat. Agricultural and Forest Meteorology, Volume 295.
36. Kissick K., M. Belkacemi, J. Malley, (eds.). (2020). Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated- Jan20.pdf.
37. Knapp, S., van der Heijden, M.G.A. (2018). A global meta-analysis of yield stability in organic and conservation agriculture. Nature Communication 3632. https://doi.org/10.1038/s41467-018-05956-1
38. Lal R (2020) Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Security volume 12, Springer Link, pages 871–876, Available at: https://link.spring- er.com/article/10.1007/s12571-020-01058-3. (2017). Improving soil health and human protein nutrition by pulse-based cropping systems. Advances in Agronomy 145:167-204.
39. Lal,R.(2009).Soil degradation as a cause for human malnutrition. Food Security 1:45-57.J.Soil and Water Consev.76:69A-72A.
40. Lal R. (2018). Saving global land resources by enhancing eco-efficiency of agro-ecosystems. J. Soil and Water Conservation 73(4):100A-106A.
41. Lal R. (2019). Promoting “ 4 per 1000” and “ Adapting African Agriculture” by south-south cooperation: conservation agriculture and sustainable intensification .Soil Tillage Research https://doi.org/10.1016/j. still.2017.12.015.
42. Lal,R.2021.Feeding the world and returning half of the agricultural land back to nature.
43. Leclère D., Obersteiner M., Barrett M. et al. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585, 551–556 (2020). https://doi.org/10.1038/s41586-020-2705-
44. Liu K, McInroy, JA, Hu CH and Kloepper JW (2018) Mixtures of plant-growth-promoting rhizobacteria enhance biological control of multiple plant diseases and plant-growth promotion in the presence of pathogens. Plant Dis. 102, 67–72. doi: 10.1094/PDIS-04-17-0478-RE
45. Malapit, H.J.; Meinzen-Dick, R.S.; Quisumbing, A.R.; & Zseleczky, L. (2020). Women: Transforming food systems for empowerment and equity. In: 2020 Global Food Policy Report. Chapter 4, Pp. 36-45. Washington, DC: International Food Policy Research Institute (IFPRI). https://doi.org/10.2499/9780896293670_04.
46. Mannakkara S, Wilkinson, S, Potangaroa, R, Resilient Post-Disaster Recovery Through Building Back Better, Routledge, 2019.
47. Mateo-Sagasta, J.; Marjani Zadeh, S.; Turral, H. 2018. More people, more food, worse water? A global review of water pollution from agriculture. Rome, Italy: FAO. 225p.
48. Morris C. and Winter M. (1999). Integrated farming systems: the third way for European agriculture? In: Land use policy 16 (1999). pp. 193-205.
49. Müller A, Schader C, Scialabba NEH, Bruggemann J, Isensee A, Erb KH, Smith P, Klocke P, Leiber F, Stolze M and Niggli U (2017). Strategies for feeding the world more sustainably with organic agriculture. Nature Communications 8: 1290.
50. Müller A. and Huppenbauer M (2016). Sufficiency, Liberal Societies and Environmental Policy in the Face of Planetary Boundaries. Gaia - Ecological Perspectives for Science and Society 25(2): 105–109. doi:10.14512/gaia.25.2.10
51. Perfecto, I., Vandermeer J. and Wright A. (2009). Nature’s Matrix: Linking Agriculture, Conservation and Food Sovereignty. Earthscan, London. 257 p.
52. Piñeiro V, Arias J, Dürr J, Elverdin P, Ibáñez AM, Kinengyere A, Opazo CM, Owoo N, Page JR, Prager SD and Torero M (2020) A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nature Sustainability volume 3, pages 809–820
53. Pretty J et al. (2018) Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1 (8). pp. 441-446. ISSN 2398-9629.
54. Reilly J, Artz D, Biddinger D, Bobiwash K, Boyle N, Brittain C, Brokaw J, Campbell J, Daniels J, Elle E, Ellis J, Fleischer S, Gibbs J, Gillespie R, Gundersen K, Gut L, Hoffman G, Joshi N, Lundin O, Winfree R (2020) Crop production in the USA is frequently limited by a lack of pollinators. Proceedings of the Royal Society B: Biological Sciences. 10.1098/rspb.2020.0922.
55. Schader C, Müller A, Scialabba NE, Hecht J, Isensee A, Erb KH, Smith P, Makkar HPS, Klocke P, Leiber F, Schwegler P, Stolze M & Niggli U. (2015). Impacts of feeding less food competing feedstuffs to live-

stock on global food system sustainability. Journal of the Royal Society Interface 12(113): 20150891.

56. Schuh, B et al. 2019, Research for AGRI Committee - The EU farming employment: current challenges and future prospects, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels, 2019.
57. Seufert V., Ramankutty N. and Foley J.A. (2012). Comparing the yields of organic and conventional agriculture. Nature 485: 229.
58. Shaw, R., Chr. Anderson, Chr. Fabricius, L. Glew, B. Loken, Sh. Mahajan, N. Olwero, J. Opperman, P. Pacheco, L. Pendleton, D, Thau, and Chr. Weber (2020). Beyond Boundaries: Insights into emerging zoonotic diseases, nature and human well-being. WWF Global Science. Internal Science Brief. Unpublished. WWF-Science-Brief-Beyond-Boundaries-Insights-into-Emerging-Zoonotic-Diseases.pdf.
59. Smith, J., Pearce, B., and Wolfe, M.S. 2012. A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renewable Agriculture and Food Systems, Volume 27, Issue 4: 323–332. DOI: https://doi.org/10.1017/S1742170511000597.
60. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyers B & Sorlin S (2015): Planetary boundaries: Guiding human development on a changing planet. Science. Vol. 347, Issue 6223, 1259855. DOI: https://doi.org/10.1126/science.1259855.
61. Syed Ab Rahman S F, Singh E, Pieterse CMJ and Schenk PM (2018) Emerging microbial biocontrol strategies for plant pathogens. Plant Sci. 267, 102–111. doi: https://doi.org/10.1016/j.plantsci.2017.11.012.
62. Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515, 518–522. https://doi.org/10.1038/nature13959.
63. Trivedi, A. (2018) Women are the secret Weapon for better Water Management Available from the World Resources Institute: https://www.wri.org/blog/2018/10/women-are-secret-weapon-better-water-management
64. van der Ploeg, J.D., et al. (2019). The Economic Potential of Agroecology: Empirical Evidence from Europe. Journal of Rural Studies, vol. 71, 2019, pp. 46-61.
65. van Huis A, Van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G and Vantomme P (2013) Edible insects: future prospects for food and feed security. FAO Forestry Paper 171 http://www.fao.org/3/i3253e/i3253e00.pdf.
66. Westhoek H, Lesschen JP, Rood, T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton MA, Oenema O (2014) Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Global Environmental Change Vol 26, pp 196-205. https://doi.org/10.1016/j.gloenvcha.2014.02.004.
67. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., Vries, W. De, Sibanda, L., … Murray, C. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet, 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
68. WRI (2018) World Resources Report. Creating a sustainable food future. A menu of solutions to feed nearly 10 billion people by 2050. Available at: https://research.wri.org/sites/default/files/2019-07/creating-sustain- able-food-future_2_5.pdf.
69. WWF (2016) Living Planet Report 2016. Risk and resilience in a new era. Available at: Living Planet Report 2016 | Pages | WWF (worldwildlife.org)Kobori, H., Primack, R. B. (2003) Participatory conservation approaches for satoyama. The traditional forest and agricultural landscape of Japan. Ambio 32: 307-311JSSA (Japan Satoyama Satoumi Assessment) (2010) Satoyama – Satoumi Ecosystems and Human Well-Being: Socio-Ecological Landscapes of Japan – Summary for Decision Makers. UNU, Tokyo, Japan.
70. WWF (2020) Living Planet report. Bending the curve of biodiversity loss. Living Planet Report 2020: Bending the curve of biodiversity loss – ICRI (icriforum.org)

This Report was prepared by members of the Scientific Group.

zef Center for Development Research University of Bonn

Cornell University

UVIC UNIVERSITAT DE VIC UNIVERSITAT CENTRAL DE CATALUNYA

LUND UNIVERSITY LUCSUS

Potsdam Institute for Climate Impact Research

AgMIP

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021

The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

CLIMATE CHANGE AND FOOD SYSTEMS

by Alisher Mirzabaev, Lennart Olsson, Rachel Bezner Kerr, Prajal Pradhan, Marta Guadalupe Rivera Ferre and Hermann Lotze-Campen

ABSTRACT

Climate change affects the functioning of all the components of food systems, often in ways that exacerbate existing predicaments and inequalities between regions of the world and groups in society. At the same time, food systems are a major cause for climate change, accounting for a third of all greenhouse gas (GHG) emissions. Therefore, food systems can and should play a much bigger role in climate policies. This policy brief highlights nine actions points for climate change adaptation and mitigation in the food systems. The policy brief shows that numerous practices, technologies, knowledge and social capital already exist for climate action in the food systems, with multiple synergies with other important goals such as the con-

ABOUT THE AUTHORS

Alisher Mirzabaev, Senior Researcher, Center for Development Research (ZEF), University of Bonn

Lennart Olsson, Professor of Geography LUCSUS, Lund University

Rachel Bezner Kerr, Professor of Global Development at Cornell University Cornell University

Prajal Pradhan, (Senior Scientist, Potsdam Institute for Climate Impact Research PIK

Marta Guadalupe Rivera Ferre, Research Fellow and Assistant Professor at the University of Vic-Central University of Catalonia

Hermann Lotze-Campen, Professor of Sustainable Land Use and Climate Change at Humboldt University Berlin, Potsdam Institute of Climate Impact Research

servation of biodiversity, safeguarding of ecosystem services, sustainable land management and reducing social and gender inequalities. Many of these solutions are presently being applied at local scales around the world, even if not at sufficient levels. Hence, the major effort for unleashing their potential would involve overcoming various technical, political-economic and structural barriers for their much wider application. Some other solutions require research and development investments now but

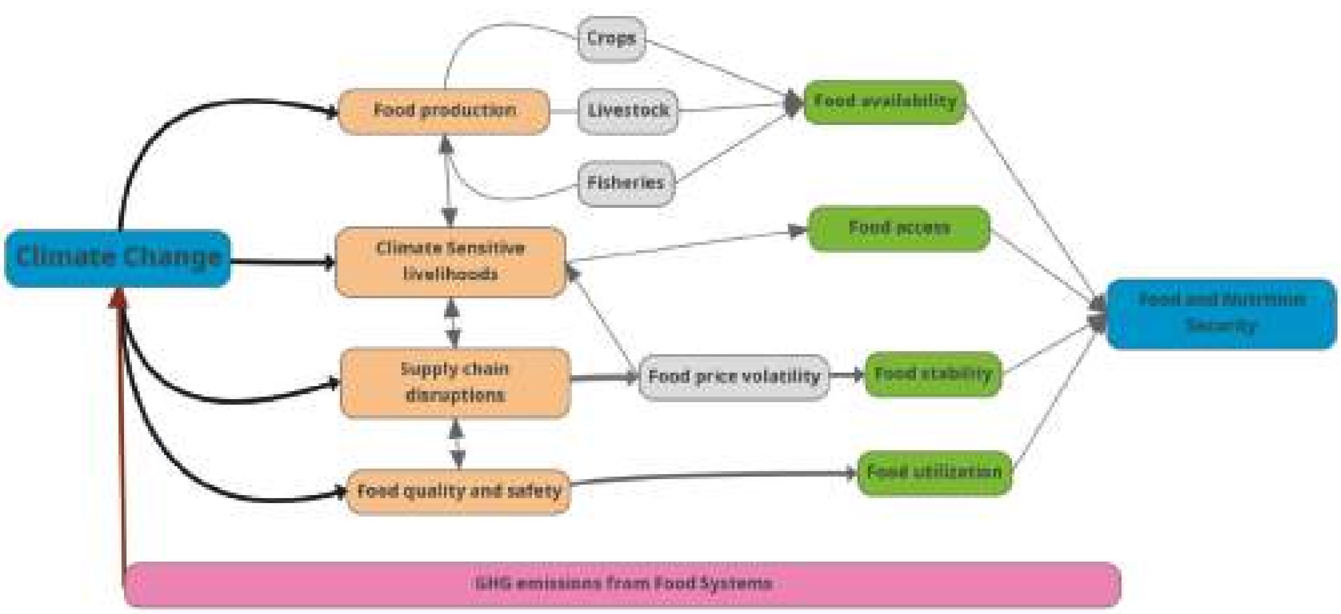
focus on helping us meet the longer-term challenges of climate change on food systems in the second half of this century when most existing food production practices will face unprecedented challenges. In the short term, these pro-poor policy changes and support systems can create a range of positive changes well beyond food systems without delay. In the long term, investments in research will help ensure food security and ecosystem integrity for coming generations.

INTRODUCTION

Climate change affects the functioning of all the components of food systems[1] which embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and recycling of food products that originate from agriculture (including livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded[2]. At the same time, food systems are a major cause of climate change, contributing about a third (21–37%) of the total GHG emissions through agriculture and land use, storage, transport, packaging, processing, retail, and consumption[3] (Figure 1).

Climate change will affect food systems differentially across world regions. While some areas, such as northern temperate regions, may even experience some beneficial changes in the short term, tropical and sub-tropical regions worldwide are expected to face changes that are detrimental to food systems. Such changes will have effects on food and nutrition security through a complex web of mechanisms (Figure 1). Critical climate variabilities that affect food and nutrition security include increasing temperatures, changing precipitation patterns and greater frequency or intensity of extreme weather events such as heatwaves, droughts and floods[3]. They impact the productivity of crops, livestock and fisheries by modulating water availability and quality, causing heat stress, and altering the pests and disease environment, including the faster spread of mycotoxins and pathogens. Increased frequency and intensity of floods and droughts can lead to considerable disruptions in food supply chains through harvest failures and infrastructure damage. The exposure of people to heatwaves, droughts and floods can harm their health and lower their productivity affecting their livelihoods and incomes, especially for those engaged in climate-sensitive sectors or working outdoors. This exposure can strongly affect more vulnerable groups in many lower-income countries, e.g. smallholder farmers, low-income households, women and children. Other factors related to climate change that

Figure 1 Linkages between climate change and food systems



affect food systems are the rise in atmospheric concentrations of CO_2 and, indirectly, land degradation, and reduction in pollination services. Changes in CO_2 levels in the atmosphere affect both crop yields and their nutrient content. Climate change will exacerbate land degradation, through increasing soil erosion especially in sloping and coastal areas, increasing soil salinity in irrigated lands, making climate more arid and prone to desertification in some dryland areas[4,5]. The potential reduction or loss of pollination services also leads to lower crop yields. Conservative estimates, which take into account these climate change impacts only partially, show that the number of people at risk of hunger may increase by 183 million people by 2050 under high emission and low adaptation scenario [i.e. under Shared Socioeconomic Pathway (SSP) 3] compared to low emission and high adaptation scenario (SSP1). An additional 150-600 million people are projected to experience various forms of micronutrient deficiency by 2050 at higher emission scenario[6–8].

The interactions between climate change and food systems have considerable repercussions across all of the dimensions of sustainable development. In fact, in six of the 17 sustainable development goals (SDGs), climate change-food systems interactions increasingly play a major role. These relate to the social goals of zero hunger (SDG 2) and gender equality (SDG5), and the four environmental goals of water resources (SDG 6), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15). Solutions addressing the challenges posed by climate change-food systems interactions can serve as a critical entry point for promoting the 2030 Agenda for sustainable development well beyond the timeline of the current SDGs[9]. Since these interactions vary according to the country's income, region, and population groups (i.e. gender, age, and location of its population), solutions prioritising women, younger, and rural people, i.e. "leaving no one behind," can better leverage achievements of SDGs[10].

HOW CLIMATE CHANGE INTERACTS WITH FOOD SYSTEMS AND FOOD SECURITY

Food availability

Considerable evidence has by now emerged indicating that climate change is already negatively affecting crop production in many areas across the world[11,12]. Reductions of 21% in total factor productivity of global agriculture since 1961 have been estimated[13]. It has been found that climate change during the last four-five decades reduced the yields of cereals by about 2%-5% on average globally compared to the situation if there was no climate change[14]. This range of about 5% lower cereal yields due to climate change was also found in regional studies, for example, for wheat and barley in Europe[15], for wheat in India[16], for maize in Africa, Central and Eastern Asia[17], and Central and South America[18]. Higher losses equalling about 5%-20% were found for millet and sorghum yields in West Africa[19], and about 5%-25% lower maize yields in Eastern and Southern Europe[20]. There is growing literature documenting the negative impacts of climate change on the yields of legumes, vegetables, and fruits in drylands, tropical and sub-tropical areas[3,21]. These losses in yields have occurred after taking coping and adaptive actions[3].

In temperate climatic zones, such as northern China, parts of Russia, northern Europe, and parts of Canada, observed climatic changes are increasing the agricultural potentials leading to higher crop production[15,17,22–25]. However, in many areas, this increased production is coming at the expense of lower yield stability due to higher weather variability between seasons. Climate change accounts for about half of food production variability globally. Presently, adaptive strategies to increase crop yields (crop breeding, improved agronomic management, adaptations based on indigenous and local knowledge, etc.) can withstand, at a global average, any impacts of climate change on crop yields. However, the acceleration of climate change can overwhelm this trend in the future; and the impacts are already experienced in many regions. Climate change increased drought-induced food production losses in southern Africa, leading to 26 million people in the region requiring humanitarian assistance in 2015-16[26]. Climate change is also increasing ocean acidification and temperatures, reducing farmed fish and shellfish production as well as wild fish catches, with some regions experiencing losses of 15-35%[3].

The impacts of climate change on food productions are projected to worsen after the 2050s, particularly under higher emission scenarios[3]. In agriculture, the biggest crop yield declines due to climate change are expected to occur in those areas which are already hot and dry, especially in the tropics and sub-tropics, as well as in the global drylands where water scarcity is projected to become more acute[5]. More recent modelling shows that previous projections of climate change impacts on future crop yields underestimated the extent of potential yield declines. For example, many crop modelling studies do not consider the effect of short-term extreme weather events. Although extreme weather events have always posed disruptions in the food systems, climate change is increasing the likelihood of simultaneous crop failures in major crop producing areas in the world[27,28]. Disruptions in storage and distribution infrastructures and on food provisioning due to extreme events systems will also impact food availability, as well as reduction in food exchanges due to lower productivity[29].

New 21st century projections by the Agricultural Model Intercomparison and Improvement Project (AgMIP)[30] using ensembles of latest-generation crop and climate models suggest markedly more pessimistic yield responses for maize, soybean, and rice compared to the original ensemble. End-of-century maize productivity is shifted from +5 to -5% (SSP126) and +1 to -23% (SSP585), explained by warmer climate projections and a revised crop model ensemble[31]. In contrast, wheat shows stronger high-latitude gains, related to higher CO_2 responses. The 'emergence' of the climate impact signal — when mean changes leave the historical variability — consistently occurs earlier in the new projections, in several main producing regions by 2030. While future yield estimates remain uncertain, these results suggest that major breadbasket regions may contend with a changing profile of climatic risks within the next few decades[31]. While many fruit, vegetable and perennial crops are understudied, higher temperatures are projected to negatively impact their production, with one study estimating a 4% reduction in fruit and vegetable production from climate change[32].

The impacts of climate change on livestock systems and fisheries are studied much less than the major crops. Nonetheless, considerable evidence indicates that increased frequency of heatwaves and droughts under climate change can lower livestock productivity and reproduction through heat stress, reduced availability of forage, increased water scarcity and the spread of livestock diseases[3,33]. Increased levels of CO_2 can favour the growth of pasture grasses, especially during rainier seasons and more humid locations [5,34]. In contrast, in many arid and semi-arid locations, the projected effects are mostly negative[33,35,36]. Climate change was found to reduce the maximum sustainable yield of several marine fish populations by about 4%[37]. Every 1°C increase in global warming was projected to decrease mean global animal biomass in the oceans by 5%[38], also redistributing fish populations away from sub-tropical and tropical seas towards poleward areas[39]. It is clear that the association between climate change and human nutrition goes beyond issues of caloric availability, and a growing challenge by 2050 will be providing nutritious and affordable diets.[32]

Food access

The impacts of climate change on agricultural production, supply chains and labour productivity in climate-sensitive sectors will influence both food prices and incomes, strongly affecting people's ability to purchase food through these price and income changes[40]. Climate change is projected to increase global cereal prices between 1% to 29 %, depending on the Shared Socioeconomic Pathway considered[3]. The reductions in the yields of legumes, fruits and vegetables will also lead to their higher prices. The impacts of these price increases on food access are not straightforward. Net food selling agricultural producers can benefit from higher food prices[41]. Higher food prices will hurt primarily the urban poor and net food buying agricultural producers[3]. Increased temperatures and more frequent heatwaves will reduce labour productivity for outdoor work and work in closed areas without air conditioning. Lower labour productivity will result in lower incomes and lower purchasing power.

Food stability

Climate change will increase the frequency of extreme water events, such as droughts, floods, hurricanes, and sea storms. Resulting inter-annual variability in food production, destruction of transportation infrastructures, and higher food price volatility can ultimately lead to more volatile global and regional food trade, undermining people's ability to access food in a stable way[3]. These disruptions could have a particularly negative impact on land-locked countries with fewer infrastructural access to global food trade and vulnerable social groups, especially in those locations without functioning and sufficient social protection schemes[12].

Food utilisation and safety

Climate change is projected to adversely impact childhood undernutrition and stunting, undernutrition-related childhood mortality and increase of disability-adjusted life years lost, with the largest risks in Africa and Asia[42]. Moreover, climate-related changes in food availability and diet quality are estimated to result in 529,000 excess climate-related deaths with about 2°C warming by 2050[32]. Most of them are projected to occur in South and East Asia. Extreme climate events will increase risks of undernutrition even on a regional scale via spikes in food prices and reduced income. Exposure to one pathway of food insecurity risks (e.g. lower yields) does not exclude exposure to other pathways (e.g. income reduction). Higher concentrations of atmospheric CO_2 reduces the protein and mineral content of cereals, reducing the quality of food and, subsequently, food utilisation[3]. Rising temperatures are improving the conditions for the spread of pathogens and mycotoxins, posing risks to human health and increasing food waste and loss[43]. Climate change is projected to increase the area of spread of mycotoxins from tropical and sub-tropical areas to temperate zones[3]. Reduction in water quality due to climate change will also negatively affect food utilisation.

Impacts of food systems on climate systems

GHG emissions from food systems are a major contributor to climate change. Food systems are responsible for about one-quarter of global GHG emissions, and even one-third if indirect effects on deforestation are included (21%-37%)[3]. Specifically, new estimates by the Food Climate Partnership[44] show that total GHG emissions from the food system were about 16 CO_2 eq yr-1 in 2018, or one-third of the total global anthropogenic GHG emissions. Three-quarters of these emissions, 13 Gt CO_2 eq yr-1, were generated either during on-farm production or in pre- and post-production activities, such as manufacturing, transport, processing, and waste disposal. The remainder was generated through land use change of natural ecosystems to agricultural land. Results further indicate that pre- and post-production emissions were proportionally more important in high-income than in low-income countries, and that during 1990-2018, land use change emissions decreased while pre- and post-production emissions increased[45].

Even if fossil fuel-related emissions were stopped immediately, continuation of the current food system emissions could make the below 2°C climate target unachievable[46]. There are significant opportunities for reducing these emissions[47], at the same time, it is important to bear in mind the food security implications when implementing climate mitigation efforts[48,49]. Without compensating policies in place, stringent, abrupt and large-scale application of mitigation options, particularly those which are land-based, can have a negative impact on global hunger and food consumption, with the detrimental impacts being especially acute for vulnerable, low-income regions that already face food security challenges[42]. However, many climate solutions can have mitigation and adaptation synergies together with other co-benefits, including for health, livelihood, and biodiversity[47,50].

SOLUTIONS FOR CLIMATE CHANGE ADAPTATION AND MITIGATION IN FOOD SYSTEMS

Based on the above assessment as well as the recent IPCC special report on Climate Change and Land[1], the following actions are proposed for uptake by governments, the private sector and civil society. These actions are of two types. Firstly, there are a wide range of both well-tested ready to go solutions, and potential solutions for climate change adaptation and mitigation in the food systems[51] (Actions 1 to 7). Many of these already available solutions are well-known and are being applied at local scales around the world, even if not at sufficient levels. Hence, the major effort for unleashing their potential would involve overcoming various technical and structural barriers for their much wider application. The second type of actions (8 and 9) focus on key promising solutions which can help us meet the longer-term challenges of climate change on the food systems in the second half of this century when most food production practices will face unprecedented challenges.

1. Amplify efforts for sustainable land management

Sustainable management of land (SLM), which includes water, supports and maintains ecosystem health, increases agricultural productivity, and contributes to climate change adaptation and mitigation[4,5]. SLM is defined as the use of land resources, including soils, water, animals and plants, to produce goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions (UN 1992 Rio Earth Summit).

There are many practical examples of SLM. Application of water-efficient irrigation methods such as sprinkler and drip irrigation can help increase resilience to increasing aridity under climate change[5]. Adoption of drought-resistant crop cultivars under diversified cropping systems is an essential adaptive strategy in many dryland areas[5]. Where suitable, agroforestry is a powerful practice for reducing soil erosion and increasing carbon sequestration, while diversifying livelihoods47. Rangeland management systems based on sustainable grazing and re-vegetation can increase rangeland resilience and long-term productivity, while supporting a wide range of ecosystem services. Agroforestry practices, shelterbelts and silvio-pasture systems help reduce soil erosion and sequester carbon, while increasing biodiversity that supports pollination and other ecosystem services[52]. SLM also includes agroecological practices, such as use of organic soil amendments, crop diversification, cover crops, intercropping, conservation agriculture practices, etc., which can have positive impacts on ecosystem services, food security and nutrition[53–57]. Indigenous knowledge and local knowledge hold a great array of practices for SLM[58]. Protection and restoration of peatlands and climate-friendly management of peatlands are a key element for ambitious emission reduction strategies[59].

Although SLM has proven positive social and economic returns, the adoption is currently insufficient. Important barriers for adoption are access to the resources for changing practices and the time required for the new practices to become productive. Introduction of payments for ecosystem services and subsidies for SLM can help. Enabling policy frameworks that include both incentives and disincentives, are needed for promoting the adoption of SLM. Land tenure considerations are a major factor contributing to the adoption of SLM4, particularly for women. Various forms of collective action are crucial for implementing SLM in both privately and communally managed lands[60], although such efforts need to be strengthened and supported by policy[61]. A greater emphasis on understanding gender-specific differences over land use and land management practices can promote SLM practices more effectively. Improved access to markets, including physical (e.g. transportation), economic (e.g. fair prices), and political (e.g. fair competition) support, raises agricultural profitability and motivates investment into climate change adaptation and SLM. Developing, enabling and promoting access to clean energy sources and technologies can contribute to reducing land degradation and mitigating climate change through decreasing the use of fuelwood and crop residues for energy, while significantly improving health for women and children[62]. Finally, looking at co-benefits between addressing climate change (adaptation and mitigation) and other urgent problems, like land degradation and biodiversity conservation, much can be gained by promoting SLM in agriculture.

2. Promote open and equitable food trade

The very heterogeneous effects of climate change on food production worldwide and the increase in extreme weather events that disrupt local food production activities highlight the importance of international food trade as a key adaptation option to this volatile environment[63,64]. At the same time, strengthening regional and local food systems, through policies and programmes which support sustainable local production, can help build a resilient food system. Such policies can include support for urban and peri-urban production, public procurement, and subsidies that encourage the application of sustainable production approaches.

Adapting to changing climate will require a combination of enhanced regional and local food trade as well as international food trade that can act as safety nets in the context of climate crises. To this aim, reducing transaction costs of food trade and maintaining transparent and well-enforced international food trade governance can strengthen food systems resilience. This will particularly include avoiding imposing export bans. Food trade and food sovereignty are complementary elements of food security, and should not be regarding as mutually exclusive, rather, transparent and fair norms need to be agreed.

Fiscal instruments (e.g. carbon taxes) need to be given high priority in order to reduce fossil fuel use in agriculture. Agricultural subsidies need to be adjusted to encourage the application of sustainable production approaches and reduce any negative effects from them through trade, and that take power differences into account, e.g. the impacts of subsidised food exports by high-income countries making it harder for farmers in low-income countries to use sustainable methods or sell their products. Trade agreement mechanisms that allow low-income countries to have an equal say in trade governance are needed.

3. Include food systems in climate financing at scale

Food systems represent a range of actors and their interlinked value-adding activities that are most impacted by climate change. Food systems are also a major source of GHG emissions. This makes food systems a high priority target for adaptation and mitigation investments. However, investments into climate change adaptation and mitigation in the food systems to date have only accounted for a tiny fraction of the total amounts of climate finance. Investments into climate change mitigation in the food systems need to be commensurate with the share of GHG emissions coming from the food systems, i.e. about a third of all mitigation funding, which is presently dominated by the energy sector and infrastructure. To illustrate, there are considerable opportunities for climate change adaptation and mitigation through investments into land restoration (e.g. reforestation, sustainable land management, re-seeding degraded rangelands) which allow for sequestering carbon in soils, increase crop and livestock productivity and provide a wide range of other ecosystem services. Estimates show that every dollar invested in land restoration yields from 3 to 6 dollars of return depending on the location across the world[65]. Investments into food value chains for reducing food waste and loss is another area with substantial mitigation and adaptation benefits. A wide range of public and private sources could be harnessed for these investments, such as increasing substantially the annual development aid dedicated to agricultural and rural development, food and nutrition security; increasing investments by the international and regional development banks into food systems, more active involvement of the private sector (e.g. green bonds) and philanthropies.

4. Strengthen social protection and empowering of the vulnerable

It is now practically impossible to fully adapt to climate change impacts. Even without climate change, extreme weather events periodically inflict significant disruptions in food systems at the local, regional and even global levels. Climate change will make these disruptions more frequent and more extensive. Therefore, it is essential to strengthen the social protection for vulnerable populations in terms of accessing food during the times of such disruptions. Social protection can involve many forms such as access to subsidised food banks, cash transfers, insurance products, pension schemes and employment guarantee schemes, weather index insurance, and universal income.

Impacts of climate change on food systems are not suffered equally by all social groups. Age, class, gender, race, ethnicity, disability, among others, are social factors that make some peoples more vulnerable than others. Actions to address such inequality and differential impacts imply, on the one hand, strengthening social protection and, on the other hand, empowering marginalised social groups through collective action. Empowering women in societies increases their capacity to improve food security under climate change, making substantial contributions to their own well-being, to that of their families and of their communities. Women's empowerment is crucial to creating effective synergies among adaptation, mitigation, and food security, including targeted agriculture programmes to change socially constructed gender biases[66]. Empowerment through collective action and groups-based approaches in the near-term has the potential to equalise relationships on the local, national and global scale[67].

5. Encourage healthy and sustainable diets

Transitioning to more healthy and sustainable diets and minimising food waste could reduce global mortality from 6% to 19% and food-related GHG emissions by 29–70% by 2050[32,68]. According to the WHO, healthy diets are essential to end all forms of malnutrition and protect from non-communicable diseases, including diabetes, heart disease, stroke and cancer. Currently, food consumption deviates from healthy diets with either too much (e.g. red meat and calories) or too little (e.g. fruits and vegetables) food and nutrition supply[69]. Healthy diets have an appropriate calorie intake, according to gender, age, and physical activity level. They are mainly composed of a diversity of plant-based foods, including coarse grains, pulses, fruits and vegetables, nuts, and seeds with low amounts of animal source foods[68]. The current diets of many high-income countries comprise a large share of animal source foods that are emission-intensive, with red meat consumption higher than the recommended value. Simultaneously, consumption of fresh fruits and vegetables is below recommended value in most countries[70]. Changes towards healthier diets have a mitigation potential of 0.7–8.0 $GtCO_2$-eq year–1 by 2050, but social, cultural, environmental, and traditional factors need to be considered to achieve this potential at broad scales[3,50]. One critical problem is that currently, healthy diets are unaffordable to broad sections of societies, even in high-income countries. Sustainable and healthy diets based on diversified intake are often linked to diversified production systems, highlighting the linkages between production and consumption[71].

To encourage dietary transitions towards healthy and sustainable diets, a full range of policy instruments from hard to soft measures are needed[68]. For example, unhealthy consumption of emission-intensive animal source foods can be disincentivised by applying taxes and charges, whereas adequate consumption of healthy foods such as fruits and vegetables can be incentivised by providing subsidies and raising consumer awareness. Importantly, policies promoting healthy diets need to pay due consideration to the differential roles of animal source foods in different parts of the world and the important role livestock can play in sustainable agriculture. For example, a recent study from Nepal, Bangladesh, and Uganda showed a reduction in stunting in young children due to adequate intake of animal source foods[72].

6. Reduce GHG emissions from the food systems

Before promoting particular changes to the food systems it is important to have an overview of where the most important potentials for reducing GHG emissions are. Agriculture is responsible for about 60% (or even 80% if the indirect land use change is included) of the total GHG emissions from the global food system[3]. One important message from a systematic meta-analysis of 38,700 farms and 1,600 food processors is the wide range of emissions – about 50-fold difference between the best and worst practices[73]. This means that political and economic measures can achieve major reductions in GHG emissions from existing food systems by applying more broadly current best practices and without waiting for new technologies or behaviour changes.

Reducing GHG emissions requires integrated interventions both at the production and consumption sides. On the production side, all those practices increasing soil organic matter contribute to both adaptation and mitigation, while decreasing soil degradation and erosion. Globally cropland soils have lost an estimated 37 GtC (136 Gt CO_2) since the Neolithic revolution[74], recapturing that lost carbon through SLM would not only contribute to climate change mitigation, it would also increase the ecological resilience of agro-ecosystems and provide opportunities for income and employment in rural societies. A wide range of practices exist, e.g. conservation agriculture practices, lower GHG emissions from fertilisers, agroecology-based approaches, agroforestry or integrating agriculture and livestock systems, which have an estimated potential to sequester 3-6.5 $GtCO_2$-eq/year[75]. In rangelands as well, extensive and mixed farming systems, through improved management practices, have the capacity to reduce emissions. Presently, there are between 200 and 500 million pastoralists in the world who act as stewards for 25% of the world's land[76].

Meat and dairy consumption is often considered a major culprit of high GHG emissions from food systems, but the discussion often lacks nuance. It is clear that the overall emissions from consumption of animal protein (mainly meat and dairy products) must be reduced to achieve mitigation targets compatible with the Paris Agreement. However, in some regions of the world, an increased consumption of animal protein would be desirable from a health perspective. It is also clear that livestock plays an important role in sustainable food systems – particularly extensive livestock can help to reduce the need for mineral fertilisers, and they can produce food from areas unsuitable for growing crops (notably drylands, cold regions, and mountainous regions). Finally, expansion of post-harvest processing, refrigeration, subsidy shifts and behavioural changes are needed to reduce food loss and waste and lower the consumption of animal products in those places where intake is too high. Incentives for emission reductions should be given to agricultural producers by applying GHG emission taxes also in agriculture, or including agriculture in existing emission trading schemes.

7. Support urban and peri-urban agriculture

Promoting urban and peri-urban agriculture (PUA) can help increase the resilience of local and regional food systems, create jobs, and under certain conditions, help reduce GHG emissions from food transportation[77] and decrease uncertainties that may be associated with disruptions in food systems. PUA includes crop production, livestock rearing, aquaculture, agroforestry, beekeeping, and horticulture within and around urban areas[78]. Around 1 billion urban inhabitants (i.e. 30% of global urban population) can be nourished by producing food in PUA79. Simultaneously, PUA can support the regionalisation of food systems, reducing emissions from food transportation[77]. Moreover, PUA is multi-functional and is practised to follow various purposes: it helps to improve food security, generate income, provide employment[80,81], especially for women and youth and reconnect urban habitants with nature cycles. Subsequently, PUA has not only a great potential to reduce poverty, and improve nutrition, but also provides a series of ecosystem services such as reduced urban heat island effects[82], or fixation of atmospheric nitrogen and carbon when using the appropriate vegetation[83], thus contributing to climate change mitigation and adaptation. PUA also comprises elements of circular economy, where household organic waste can be used as livestock and poultry feed rather than treated as waste[84], subsequently reducing environmental pollution and GHG emissions. PUA contributes to increasing the resilience of urban poor households to food price shocks. Previous research on PUA showed that it was the main and only economic activity of poor urban households in many low-income countries. And even when PUA is not the main economic activity of poor urban households, it made a significant contribution to smoothening seasonal food consumption shocks among the urban poor[80].

8. Invest in research

There have been tremendous advances in better understanding of the interactions between climate change and food systems in recent decades[1,85]. These investments in research and science need to be expanded into the future, not least to ensure viable agricultural systems in the long term when climate change will expose current staple food crops to unprecedented stress. Areas for investments include agroecological approaches to food production, which have received much lower investment,[97] breeding of drought-resistant crop cultivars and cultivars with improved nitrogen use to avoid emission of N_2O[86], improved understanding of climate change impacts on both staple and non-staple foods, including impacts on nutritious values of crops[87], particularly vegetables and fruits, and the subsequent implications for the healthy diets and the full costs of healthy diets. Along with these environmental dimensions, increased investments into research on social and economic impacts of climate change are needed, for example, on such areas as understanding the impacts of climate change and mitigation and adaptation options on vulnerable groups, research on participatory and transdisciplinary approaches to facilitate dialogue between indigenous and scientific knowledge, research on collective action, social innovation and mechanisms to increase food security.

9. Support perennial crop development and cultivation

About 87% of the world's harvested area is cultivated with annual crops, mainly grains (cereals, oilseeds, and pulses) that are terminated and resown every year/season[88]. A shift to perennial grain crops would drastically cut GHG emissions from agriculture, and even turn cropping into a carbon sink, while significantly reducing erosion and nutrient leakage. Continued climate change is rendering our existing cultivars increasingly vulnerable to stress and ultimately unfit for many regions of the world[89]. New perennial cultivars have the potential to create cropping systems that are genuinely adapted for the climatic conditions towards the second half of this century. Perennial crops have the potential to drastically reduce the costs of farming by cutting the need for external inputs (seeds, fertilisers, pesticides, machinery, energy, and labour) and hence generate social and economic advantages particularly to farmers and rural societies[90].

Development of new perennial grain crops through de novo domestication and wide hybridisation have advanced tremendously in the last decade thanks to scientific and technological advancements such as genomic selection technology[91]. The key benefits of perennial crops are that their widespread root systems can help sequester carbon in the soils for extended periods of time, water and minerals are used by perennial plants more efficiently, weeds are effectively managed9[0,92]. They are also exceptionally drought resistant and can bring soil erosion and nutrient leaching to practical minimum[93]. There are already commercial cultivars of perennial rice[94] and successful semi-commercial experiments with perennial Kernza, a wheat relative[95]. The yields of Kernza are still low compared to conventional wheat, but continued breeding can result in a competitive perennial alternative to wheat in 20-25 years[96]. A range of other crops is in the pipeline for domestication and breeding as perennial crops such as barley, oilseeds, and pulses. Equally important is the development of perennial polycultures, such as intercropping of perennial grains and legumes, making the system more or less self-sufficient in nitrogen. These results are proofs of concept that high yielding perennial cultivars can be developed in the timeframe of a few decades, but research on all aspects of such a "perennial revolution" are urgently needed.

CONCLUSION

This policy brief has two central messages. The bad news is that climate change is projected to affect food systems around the world significantly, often in ways that exacerbate existing frailties/weaknesses and inequalities between regions of the world and groups in society. The good news is that many practices, technologies, knowledge and social capital already exist to address climate change constructively, in terms of both mitigation and adaptation, as well as synergies between them and co-benefits with other important goals such as the conservation of biodiversity and other ecosystem services. Therefore, food systems, can and should play a much bigger role in climate policies. In the short term, pro-poor policy changes and support systems can unleash a range of positive changes well beyond food systems without delay. In the long term, there is an urgent need to invest in research for ensuring food security and ecosystem integrity for coming generations.

REFERENCES

1. IPCC. Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. (2019).
2. von Braun, J., Afsana, K., Fresco, L. O., Hassan, M. & Torero, M. Food Systems – Definition, Concept and Application for the UN Food Systems Summit. A paper from the Scientific Group of the UN Food Systems Summit. (2021).
3. Mbow, C. et al. Food Security. in Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (eds. [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Z., R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. P. & P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. M.) (2019).
4. Olsson, L. et al. Land Degradation. in Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019).
5. Mirzabaev, A. et al. Desertification. in Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (eds. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. P., D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. P. & J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. M.) (2019).
6. Myers, S. S. et al. Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. Annual Review of Public Health 38, 259–277 (2017).
7. Zhu, C. et al. Carbon dioxide (CO2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Sci. Adv. 4, (2018).
8. Medek, D. E., Schwartz, J. & Myers, S. S. Estimated effects of future atmospheric co2 concentrations on protein intake and the risk of protein deficiency by country and region. Environ. Health Perspect. 125, (2017).
9. Pradhan, P., Costa, L., Rybski, D., Lucht, W. & Kropp, J. P. A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earth's Futur. 5, 1169–1179 (2017).
10. Warchold, A., Pradhan, P. & Kropp, J. P. Variations in sustainable development goal interactions: Population, regional, and income disaggregation. Sustain. Dev. 29, 285–299 (2021).
11. Kim, W., Iizumi, T. & Nishimori, M. Global patterns of crop production losses associated with droughts from 1983 to 2009. J. Appl. Meteorol. Climatol. 58, 1233–1244 (2019).
12. FAO. The future of food and agriculture – Alternative pathways to 2050. (2018).
13. Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G. & Lobell, D. B. Anthropogenic climate change has slowed global agricultural productivity growth. Nat. Clim. Chang. 11, 306–312 (2021).
14. Iizumi, T., Shin, Y., Kim, W., Kim, M. & Choi, J. Global crop yield forecasting using seasonal climate information from a multi-model ensemble. Clim. Serv. 11, 13–23 (2018).
15. Moore, F. C. & Lobell, D. B. The fingerprint of climate trends on european crop yields. Proc. Natl. Acad. Sci. U. S. A. 112, 2970–2975 (2015).
16. Gupta, R., Somanathan, E. & Dey, S. Global warming and local air pollution have reduced wheat yields in India. Clim. Change 140, 593–604 (2017).
17. Ray, D. K. et al. Climate change has likely already affected global food production. PLoS One 14, e0217148 (2019).
18. Verón, S. R., de Abelleyra, D. & Lobell, D. B. Impacts of precipitation and temperature on crop yields in the Pampas. Clim. Change 130, 235–245 (2015).
19. Sultan, B., Defrance, D. & Iizumi, T. Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci. Rep. 9, 1–15 (2019).
20. Agnolucci, P. & De Lipsis, V. Long-run trend in agricultural yield and climatic factors in Europe. Clim. Change 159, 385–405 (2020).
21. Scheelbeek, P. F. D. et al. Effect of environmental changes on vegetable and legume yields and nutritional quality. Proc. Natl. Acad. Sci. U. S. A. 115, 6804–6809 (2018).
22. Potopová, V. et al. The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014. Int. J. Climatol. 37, 1648–1664 (2017).
23. Meng, Q. et al. The benefits of recent warming for maize production in high latitude China. Climatic Change 122, 341–349 (2014).
24. Wang, H. & Hijmans, R. J. Climate change and geographic shifts in rice production in China. Environ. Res. Commun. 1, 011008 (2019).
25. Bisbis, M. B., Gruda, N. & Blanke, M. Potential impacts of climate change on vegetable produc-

tion and product quality – A review. Journal of Cleaner Production 170, 1602–1620 (2018).
26. Funk, C. et al. 18. Anthropogenic enhancement of moderate-to-strong El Niño events likely contributed to drought and poor harvests in southern Africa during 2016. Bull. Am. Meteorol. Soc. 99, S91–S96 (2018).
27. Anderson, W. B., Seager, R., Baethgen, W., Cane, M. & You, L. Synchronous crop failures and climate-forced production variability. Sci. Adv. 5, eaaw1976 (2019).
28. Heino, M., Guillaume, J. H. A., Müller, C., Iizumi, T. & Kummu, M. A multi-model analysis of teleconnected crop yield variability in a range of cropping systems. Earth Syst. Dyn. 11, 113–128 (2020).
29. Rivera Ferre, M. G. Impacts of Climate Change on Food Availability: Distribution and Exchange of Food BT - Global Environmental Change. in (ed. Freedman, B.) 701–707 (Springer Netherlands, 2014). doi:10.1007/978-94-007-5784-4_119
30. Rosenzweig, C., Mutter, C. Z. & Contreras, E. M. Handbook of Climate Change and Agroecosystems -- Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research (In 2 Parts). Series on Climate Change Impacts, Adaptation, and Mitigation (Vol. 5). (World Scientific Publishing, 2021).
31. Jägermeyr, J. et al. Climate change signal in global agriculture emerges earlier in new generation of climate and crop models. Nat. Food(under Rev.
32. Springmann, M. et al. Global and regional health effects of future food production under climate change: A modelling study. Lancet 387, 1937–1946 (2016).
33. Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T. & Woznicki, S. A. Climate change and livestock: Impacts, adaptation, and mitigation. Clim. Risk Manag. 16, 145–163 (2017).
34. Herrero, M. et al. Climate change and pastoralism: Impacts, consequences and adaptation. OIE Rev. Sci. Tech. 35, 417–433 (2016).
35. Fao. Climate change and food systems: Global assessments and implications for food security and trade. (2015).
36. Boone, R. B., Conant, R. T., Sircely, J., Thornton, P. K. & Herrero, M. Climate change impacts on selected global rangeland ecosystem services. Glob. Chang. Biol. 24, 1382–1393 (2018).
37. Free, C. M. et al. Impacts of historical warming on marine fisheries production. Science (80-.). 363, 979 LP – 983 (2019).
38. Lotze, H. K. et al. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proc. Natl. Acad. Sci. U. S. A. 116, 12907–12912 (2019).
39. Oremus, K. L. et al. Governance challenges for tropical nations losing fish species due to climate change. Nat. Sustain. 3, 277–280 (2020).
40. Baarsch, F. et al. The impact of climate change on incomes and convergence in Africa. World Dev. 126, 104699 (2020).
41. Hertel, T. W., Burke, M. B. & Lobell, D. B. The poverty implications of climate-induced crop yield changes by 2030. Glob. Environ. Chang. 20, 577–585 (2010).
42. Hasegawa, T. et al. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Chang. 8, 699–703 (2018).
43. Battilani, P. Recent advances in modeling the risk of mycotoxin contamination in crops. Current Opinion in Food Science 11, 10–15 (2016).
44. Rosenzweig, C., F., Tubiello, D., Sandalow, Benoit, P. & Hayek, M. Finding and Fixing Food System Emissions: The Double Helix of Science and Policy. Environ. Res. Lett. (2021).
45. Tubiello F. N. et al. Greenhouse Gas Emissions from Food Systems: Building the Evidence Base. Environ. Res. Lett. (2021).
46. Clark, M. A. et al. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science (80-.). 370, 705 LP – 708 (2020).
47. Smith, P., J. et al. nterlinkages Between Desertification, Land Degradation Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. in Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (eds. [P.R. Shukla, J. Skea, E. C. B., V. Masson-Delmotte, H.- O. Portner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. H., S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. & Press, I.) (2019).
48. Frank, S. et al. Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. Nat. Clim. Chang. 9, 66–72 (2019).
49. Hasegawa, T. et al. Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change 8, 699–703 (2018).
50. Rosenzweig, C. et al. Climate change responses benefit from a global food system approach. Nat. Food 1, 94–97 (2020).
51. Herrero, M. et al. Innovation can accelerate the transition towards a sustainable food system. Nat. Food 1, 266–272 (2020).
52. Kuyah, S. et al. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan

Africa. A meta-analysis. Agron. Sustain. Dev. 39, 1–18 (2019).
53. Bezner Kerr, R. et al. Can agroecology improve food security and nutrition? A review. Glob. Food Sec. 29, 100540 (2021).
54. Beillouin, D., Ben-Ari, T. & Makowski, D. Evidence map of crop diversification strategies at the global scale. Environmental Research Letters 14, 123001 (2019).
55. Muller, A. et al. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8, 1–13 (2017).
56. Tamburini, G. et al. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6, eaba1715 (2020).
57. Kremen, C. & Merenlender, A. M. Landscapes that work for biodiversity and people. Science 362, (2018).
58. Rivera-ferre, M. G. et al. Traditional agricultural knowledge in land management: the potential contributions of ethnographic research to climate change adaptation in India, Bangladesh, Nepal, and Pakistan. Climate and Development (2021). doi:10.1080/17565529.2020.1848780
59. Humpenöder, F. et al. Peatland protection and restoration are key for climate change mitigation. Environ. Res. Lett. 15, 104093 (2020).
60. Pretty, J. Social Capital and the Collective Management of Resources. Science 302, 1912–1914 (2003).
61. Isgren, E. 'If the change is going to happen it's not by us'': Exploring the role of NGOs in the politicization of Ugandan agriculture'. J. Rural Stud. 63, 180–189 (2018).
62. Sana, A., Meda, N., Badoum, G., Kafando, B. & Bouland, C. Primary cooking fuel choice and respiratory health outcomes among women in charge of household cooking in ouagadougou, Burkina faso: Cross-sectional study. Int. J. Environ. Res. Public Health 16, (2019).
63. Van Meijl, H. et al. Comparing impacts of climate change and mitigation on global agriculture by 2050. Environ. Res. Lett. 13, 064021 (2018).
64. Stevanović, M. et al. The impact of high-end climate change on agricultural welfare. Sci. Adv. 2, e1501452 (2016).
65. Nkonya, E. et al. Global cost of land degradation. Economics of Land Degradation and Improvement - A Global Assessment for Sustainable Development (2015). doi:10.1007/978-3-319-19168-3_6
66. Kerr, R. B., Chilanga, E., Nyantakyi-Frimpong, H., Luginaah, I. & Lupafya, E. Integrated agriculture programs to address malnutrition in northern Malawi. BMC Public Health 16, 1–14 (2016).
67. Ringler, C., Quisumbing, A. R., Bryan, E. & Meinzen-Dick, R. Enhancing Women's Assets to Manage Risk Under Climate Change: Potential for Group-based Approaches. (International Food Policy Research Institute, Washington, DC, USA, 65 pp., 2014).
68. Willett, W. et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet 393, 447–492 (2019).
69. Pradhan, P. & Kropp, J. P. Interplay between diets, health, and climate change. Sustain. 12, 3878 (2020).
70. Bodirsky, B. L., Dietrich, J. P., Martinelli, E., Stenstad, A., Pradhan, P. & Gabrysch, S., Mishra, A., Weindl, I., Le Mouël, C., Rolinski, S., Baumstark, L., Wang, X., Waid, J. L., Lotze-Campen, H., Popp, A. The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. Sci. Rep. (2020).
71. Chepkoech, W., Mungai, N. W., Stöber, S. & Lotze-Campen, H. Understanding adaptive capacity of smallholder African indigenous vegetable farmers to climate change in Kenya. Clim. Risk Manag. 27, 100204 (2020).
72. Zaharia, S. et al. Sustained intake of animal-sourced foods is associated with less stunting in young children. Nat. Food 2, 246–254 (2021).
73. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. Science (80-.). 360, 987–992 (2018).
74. Sanderman, J., Hengl, T. & Fiske, G. J. Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. 114, 9575 LP – 9580 (2017).
75. Arneth, A. et al. Restoring degraded lands. Annu. Rev. Environ. Resour. 46, (2021).
76. Niamir-Fuller, M. Towards sustainability in the extensive and intensive livestock sectors. OIE Rev. Sci. Tech. 35, 371–387 (2016).
77. Pradhan, P. et al. Urban Food Systems: How Regionalization Can Contribute to Climate Change Mitigation. Environ. Sci. Technol. 54, 10551–10560 (2020).
78. Clinton, N. et al. A Global Geospatial Ecosystem Services Estimate of Urban Agriculture. Earth's Futur. 6, 40–60 (2018).
79. Kriewald, S., Pradhan, P., Costa, L., Ros, A. G. C. & Kropp, J. P. Hungry cities: How local food self-sufficiency relates to climate change, diets, and urbanisation. Environ. Res. Lett. 14, 094007 (2019).
80. Poulsen, M. N., McNab, P. R., Clayton, M. L. & Neff, R. A. A systematic review of urban agriculture and food security impacts in low-income countries. Food Policy 55, 131–146 (2015).
81. Warren, E., Hawkesworth, S. & Knai, C. Investigating the association between urban agriculture and food security, dietary diversity, and nutritional status: A systematic literature review. Food Policy 53, 54–66 (2015).

82. Li, D., Bou-Zeid, E. & Oppenheimer, M. The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ. Res. Lett. 9, 055002 (2014).
83. Beniston, J. & Lal, R. Improving soil quality for urban agriculture in the north central U.S. in Carbon Sequestration in Urban Ecosystems 279–313 (Springer Netherlands, 2012). doi:10.1007/978-94-007-2366-5_15
84. Ibrahim, A. A. M. & Elariane, S. A. Feasibility tools for urban animal husbandry in cities: case of greater Cairo. Urban Res. Pract. 11, 111–138 (2018).
85. Wheeler, T. & Von Braun, J. Climate change impacts on global food security. Science 341, 508–513 (2013).
86. Coskun, D., Britto, D. T., Shi, W. & Kronzucker, H. J. Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. Nature Plants 3, 1–10 (2017).
87. Soares, J. C., Santos, C. S., Carvalho, S. M. P., Pintado, M. M. & Vasconcelos, M. W. Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. Plant and Soil 443, 1–26 (2019).
88. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles 22, (2008).
89. Altieri, M. A., Nicholls, C. I., Henao, A. & Lana, M. A. Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development 35, 869–890 (2015).
90. Crews, T. E., Carton, W. & Olsson, L. Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. Glob. Sustain. 1, (2018).
91. Crain, J., DeHaan, L. & Poland, J. Genomic prediction enables rapid selection of high-performing genets in an intermediate wheatgrass breeding program. Plant Genome e20080 (2021). doi:10.1002/tpg2.20080
92. DeHaan, L. et al. Roadmap for Accelerated Domestication of an Emerging Perennial Grain Crop. Trends in Plant Science 25, 525–537 (2020).
93. Crews, T. E. et al. Going where no grains have gone before: From early to mid-succession. Agriculture, Ecosystems and Environment 223, 223–238 (2016).
94. Zhang, Y. et al. An innovated crop management scheme for perennial rice cropping system and its impacts on sustainable rice production. Eur. J. Agron. 122, 126186 (2021).
95. Lanker, M., Bell, M. & Picasso, V. D. Farmer perspectives and experiences introducing the novel perennial grain Kernza intermediate wheatgrass in the US Midwest. Renew. Agric. Food Syst. 35, 653–662 (2020).
96. Bajgain, P. et al. ‘MN-Clearwater’, the first food-grade intermediate wheatgrass (Kernza perennial grain) cultivar. J. Plant Regist. 14, 288–297 (2020).
97. HLPE, 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. FAO, Rome, pp. 1–162.

The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

WATER FOR FOOD SYSTEMS AND NUTRITION

by Claudia Ringler, Mure Agbonlahor, Kaleab Baye, Jennie Barron, Mohsin Hafeez, Jan Lundqvist, J.V. Meenakshi, Lyla Mehta, Dawit Mekonnen, Franz Rojas-Ortuste, Aliya Tankibayeva and Stefan Uhlenbrook

ABOUT THE AUTHORS

Claudia Ringler, Deputy Director of Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), Washington DC

Mure Agbonlahor, Senior Agricultural Production and Marketing Officer, Africa Union Commission, Burkina Faso

Jennie Barron, Professor, Swedish University of Agricultural Sciences, Sweden

Kaleab Baye, Director of the Center for Food Science and Nutrition at Addis Ababa University, Ethiopia

Mohsin Hafeez, Country Representative, International Water Management Institute, Pakistan

Jan Lundqvist, Professor, Senior Scientific Advisor, Stockholm International Water Institute, Sweden

J.V. Meenakshi, Professor of Economics, University of Delhi, India

Lyla Mehta, Professorial Fellow, Institute of Development Studies, United Kingdom, Norwegian University of Lifes, Norway

Dawit Mekonnen, Research Fellow, International Food Policy Research Institute, Ethiopia

Aliya Tankibayeva, Professor, Head of the Department of Epidemiology and Hygiene Al-Farabi Kazakh National University, Kazakhstan

Stefan Uhlenbrook, Program Director, CGIAR Research Program on Water, Land and Ecosystems (WLE), Strategic Program Director (IWMI), Sri Lanka

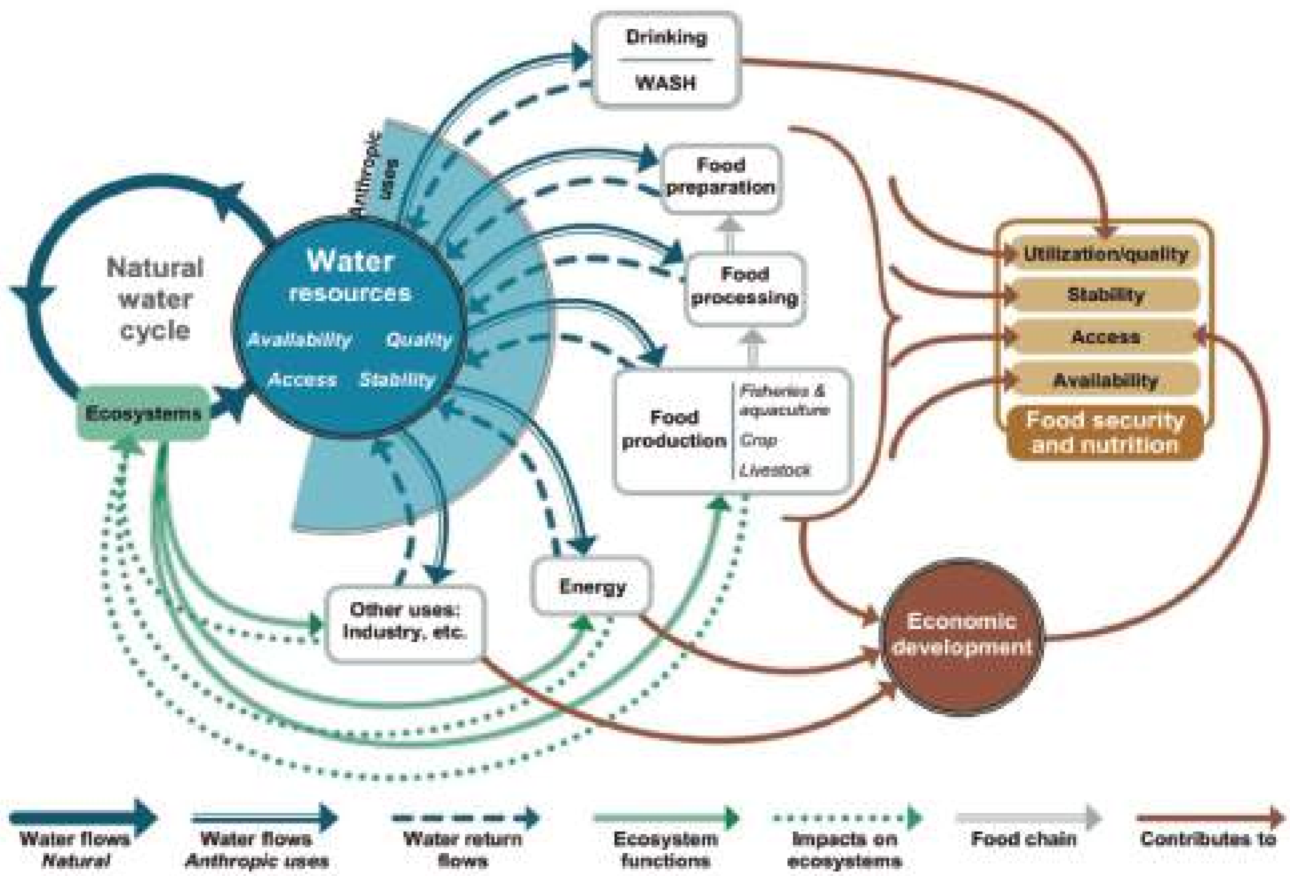
ABSTRACT

Access to sufficient and clean freshwater is essential for all life. Water is also essential for food system functioning: as a key input into food production, but also in processing and preparation, and as a food itself. Water scarcity and pollution are growing, affecting poorer populations, particularly food producers. Malnutrition levels are also on the rise, and this is closely linked to water scarcity. The achievement of Sustainable Development Goal (SDG) 2 and SDG 6 are co-dependent. Solutions to jointly improve food systems and water security outcomes that the United Nations Food Security Summit (UNFSS) should consider include: 1) strengthening efforts to retain water-based ecosystems and their functions; 2) improving agricultural water management for better diets for all; 3) reducing water and food losses beyond the farmgate; 4) coordinating water with nutrition and health interventions; 5) increasing the environmental sustainability of food systems; 6) explicitly addressing social inequities in water-nutrition linkages; and 7) improving data quality and monitoring for water-food system linkages, drawing on innovations in information and communications technology (ICT).

INTRODUCTION

Water is essential for all life and is integral to the function and productivity of the Earth's ecosystems, which depend on a complex cycle of continuous movement of water between the Earth and the atmosphere. Water is integral to food systems and improved food systems are essential to meet SDG 6 on water and sanitation. As described by the High-Level Panel of Experts on Food Security and Nutrition (HLPE) and illustrated in Figure 1, the key dimensions of water that are of importance for humanity are its availability, access, stability, and quality. These have multiple, close linkages and feedback loops with food systems, which can be defined as the activities involved in the production, processing, distribution, preparation, and consumption of food within a wider socioeconomic, political, and environmental context. For example, waste streams from food processing often re-enter water bodies, affecting other components of food systems, such as drinking water supply (water is itself essential for all bodily functions and processes, and is an important source of nutrients), as well as water-based and water-related ecosystems.

Figure 1 Linkages between climate change and food systems



More than 70 percent of all freshwater withdrawals are currently used for agriculture, and about 85 percent of withdrawn resources are consumed in irrigated agricultural production. With these resources, irrigated crop areas generate 40 percent of global food production on less than one-third of global harvested area. Another key water-food system linkage is water supply for WASH (water, sanitation and hygiene), which is important for human health, can support nutrition outcomes, particularly if combined with other interventions, and is a basic human right, as is the right to food. Water is also essential for agricultural processing and for food preparation.

Climate change and other environmental and societal changes (e.g. land use changes, biodiversity loss, urbanisation, and changing lifestyles and diets) are impacting the dynamics of natural water cycles and water resource availability with impacts on food systems. More than half of all natural wetland areas have been lost due to human activity since 1900 and forest degradation affects streamflow regulation. At the same time, the growing frequency and severity of floods and droughts in many regions of the world increase competition over water resources. This calls for changes in water management, including increased water productivity, integrated storage solutions, accelerated land restoration as well as smarter water distribution to support food systems, while also reducing impacts on the domestic, industrial, energy, and environmental water use sectors.

SDG 2 AND SDG 6 CAN ONLY BE ACHIEVED IF THE WATER AND FOOD SYSTEMS COMMUNITIES WORK TOGETHER

Water scarcity and pollution are growing, affecting poorer populations, particularly food producers

Freshwater-related ecosystems include wetlands, rivers, aquifers, and lakes sustaining biodiversity and life. Although they cover less than 1 percent of the Earth's surface, these habitats host approximately one-third of vertebrate species and 10 percent of all species, including mammals, birds, and fish. Water-related ecosystems are also vital for the function of all terrestrial ecosystems, providing regulating, provisioning, and cultural services. Furthermore, water is essential for energy production, accounting for 85 percent of global renewable electricity generation in 2015, and is also key for commerce and industry. Notably, de-carbonising the energy system can also impact the water system, particularly in the case of increasing hydropower and biofuel. Progress on achieving the water and sanitation targets of SDG 6 has been unsatisfactory and uneven (see Appendix 1 for SDG 6 targets). More than 2 billion people live in places with high water stress, : by 2050, every second person, half the world's grain production, and close to half the globe's Gross Domestic Product might well be at risk from water stress. In 2017, approximately 2.2 billion people lacked access to safely managed drinking water, and 4.2 billion people lacked access to safely managed sanitation services. One in ten people lacked basic services, including the 144 million people who drank untreated surface water, mostly in sub-Saharan Africa. Poor women and girls, who are responsible for more than 70 percent of all water collection, spend about 200 million hours a day on this task, reducing their learning opportunities and undermining their health and livelihood opportunities.

Farmers across the world, but particularly in sub-Saharan Africa, continue to rely heavily on rainfall for food production. More than 62 million hectares of crop and pastureland experience high to very high water stress and drought, affecting about 300 million farm households. With climate change, temperatures and crop evaporation levels are increasing and there is growing uncertainty about the timing, duration and quantity of rainfall, increasing the risks of producing food and undermining the livelihood security of the majority of rural people. With respect to the other SDG 6 targets, such as water quality, water use efficiency, water dependent ecosystems, and integrated water management, progress has been slow and is often not well understood due to the lack of effective monitoring mechanisms and insufficient data. New, integrated approaches and reinforced efforts are urgently needed.

While water availability differs dramatically around the globe, differences in access are more often due to politics, public policy, and flawed water management strategies as well as exclusions due to geography (i.e. remote rural areas), gender, ethnicity, caste, race, and class. In many cases, water does flow uphill to power and money. Furthermore, increasing urbanisation and changing diets are changing the demand and supply of water resources for food systems and aggravating water stress in many parts of the world, particularly in water-scarce areas of low/middle income countries where coping capacity is often insufficient.

Malnutrition levels are on the rise and are closely linked to water scarcity

An estimated 690 million people or 8.9 percent of the global population were undernourished in 2019, prior to the COVID-19 pandemic, whereby this number has certainly increased since. Moreover, 144 million children below the age of five were stunted, 48 million were wasted, and another 38 million were overweight. Climate change, associated conflict, and lack of sufficient water for food production, including irrigation for fruits and vegetable production, are key contributors to unaffordable diets and overall levels of undernutrition. At the same time, overweight continues to dramatically increase around the globe, including in children. Latin America in particular suffers from the associated public health burden. Overall, rural areas currently experience the most rapid rate of increase. Given these trends, neither the 2025 World Health Assembly nutrition targets nor the 2030 SDG nutrition targets will be met. As with inequities in access to water, inequities in access to food and nutrition are highest in rural areas.

SDG 2 and SDG 6 targets are co-dependent

Ending hunger and malnutrition requires access to safe drinking water (SDG 6.1) as well as equitable sanitation and hygiene (SDG 6.2). The underlying productivity (SDG 2.3) and sustainability (SDG 2.4) of agricultural systems are also dependent on adequate availability (SDG 6.4 and 6.6) of good quality (SDG 6.3) water. Moreover, water and related ecosystems (e.g. wetlands in SDG 6.6), which are embedded in sustainable landscapes, are important contributors to sustainable agriculture (SDG 2.4).

A key contributor to poor nutritional outcomes in subsistence farming households in low-income countries is the seasonality of production, leading to seasonality of diets, which can affect pregnancy outcomes and child growth. Well-managed irrigation systems can buffer seasonal gaps in diets, contributing to improved food security and nutritional outcomes, for example, through homestead gardening.

It is equally important to stress the importance of changes in food systems for meeting SDG 6 targets: through reducing food loss and waste in food value chains (SDG 12.3), lowering pollution from slaughterhouses, food processing, and food preparation, and considering environmental sustainability in food-based dietary guidelines. All of these actions will be essential to meet SDG 6 targets (Appendix 1).

SOLUTIONS TO IMPROVE FOOD SYSTEMS OUTCOMES AND IMPROVED WATER SECURITY

Based on the above assessment as well as recent water-food system reviews, the following actions are proposed for uptake by governments, the private sector, and civil society.

1. Strengthen efforts to retain water-based ecosystems and their functions

The ecological processes underlying the movement, storage, and transformation of water are under severe threat from deforestation, erosion, and pollution, with impacts on local, regional, and global water cycles. In addition to a direct halt to deforestation and destruction of water-based ecosystem, nature-based solutions that use or mimic natural processes to enhance water availability (e.g. groundwater recharge), improve water quality (e.g. riparian buffer strips), and reduce risks associated with water-related disasters and climate change (e.g. floodplain restoration) should be strengthened. Setting limits to water consumption, particularly in water-stressed regions, will be necessary to stay within sustainable water use limits.

2. Improve agricultural water management for better diets for all

Around 3 billion people on this planet cannot afford a healthy diet, particularly dairy, fruits, vegetables, and protein-rich foods.Both rainfed and irrigated systems play essential roles in lowering the prices of nutrient-dense foods, growing incomes to afford these foods, and strengthening diversity of foods available in local markets .

2.1 Strengthen the climate resilience of rainfed food systems

Rainfed systems produce the bulk of food, fodder, and fibre, and most animal feed is produced under rainfed conditions. These systems are under severe and growing stress from climate change, including extreme weather. This can be addressed, to some extent, through structural measures (e.g. terracing, soil bunds), investment in breeding, improved agronomic practices, better incentives (e.g. payments for watershed conservation), and strong institutions (e.g. watershed committees).

2.2 Strengthen the nutrient density of irrigated agriculture

As irrigation accounts for the largest share of freshwater withdrawals by humans, the potential for water conservation is also largest in this sector. Irrigation development needs to take place keeping environmental limits – which are increasingly affected by climate change – in mind, and this includes reining in groundwater depletion. The potential for increasing water and nutrition productivity in irrigation remains large. It includes crop breeding for transpiration efficiency, climate resilience and micronutrients, integrated storage solutions – such as joint use of grey and green infrastructure –advanced irrigation technology, and automated irrigation systems. There are clear trade-offs between nutrient density of foods and irrigation water use. Fruits and vegetable yields depend on frequent water applications in many parts of the world (but the water content of the end product also tends to be high), and tend to receive high pesticide applications that pollute water resources. Many livestock products are highly water-intensive due to animal feeds. Awareness raising and social learning interventions can help internalise the water externality of water-intensive diets. Improved coordination of water with other agricultural inputs can also enhance yield per drop of water. This requires access to technology packages as well as to better agricultural information, which is increasingly supported by ICTs. Moreover, subsidies for water-intensive crops, such as rice, milk, and sugar should be removed. For water-scarce countries, importing virtual water via food and other commodities will remain essential.

2.3 Address water pollution to improve food production, food safety, and water-based ecosystems

Globally, 80 percent of municipal sewage and industrial wastewater with heavy metals, solvents, toxic sludge, pharmaceuticals, and other waste, are directly discharged into water bodies, affecting the safety of food, particularly vegetable production, and also, directly, human health. Agriculture also directly pollutes aquatic ecosystems and risks food production with pesticides, organic matter, fertilisers, sediments, pathogens, and saline drainage. Key measures to address agricultural and overall water pollution include breeding crops with higher crop nutrient use efficiency, better agronomic practices, the expansion of nature-based solutions for pollution management, low-cost pollution monitoring systems, improved incentive structures for pollution abatement, and continued investment and innovation in wastewater treatment, including approaches such as the 3R (reduce, reuse, and recycle) of the circular economy across the entire food system .

3. Reduce water and food losses beyond the farmgate

Irrigated agriculture is often focused on high-value crops with a higher share of marketed surplus compared to rainfed agriculture. At the same time, many irrigated crops, such as fruits and vegetables, are time-sensitive perishable products that require efficient market linkages to consumption centres. Strengthening market linkages includes investment in physical infrastructure that supports on-farm production (irrigation, energy, transportation, pre- and post-harvest storage), efficient trading and exchange (telecommunications, covered markets), value addition (agro-processing and packaging facilities), and improved transportation and bulk storage. Investments are also needed in ICTs that facilitate farmers' access to localised and tailored information about weather, water consumption, diseases, yield, and input and output prices .

4. Coordinate water with nutrition and health interventions

4.1 Strengthen institutional coordination and develop joint programs

Governance and management of water for various uses and functions, as shown in Figure 1, follow different institutional arrangements. Similarly, professionals engaged in various roles within water-related institutions have different kinds of training and experiences. Few irrigation engineers have a professional background or skills related to WASH, and few WASH professionals have the technical skills needed to design water infrastructure for multiple uses. The notion of Integrated Water Resources Management (SDG 6.5) has been promoted as a principle to overcome problems due to sectoral division. Coordination at the lowest appropriate levels is urgently needed between WASH and irrigation for improved food security, nutrition, health outcomes and also to strengthen women's agency. Multiple use water systems can increase food security and WASH outcomes. A further example is the MiAgua programme in Bolivia supported by the development bank of Latin America (CAF), which included rural water supply, climate change adaptation measures such as watershed protection, and micro-irrigation projects for small-scale agriculture. MiAgua benefited 2.25 million people and contributed to increasing rural water coverage from 52 percent in 2011 to 80 percent in 2020.

4.2 Implement nutrition-sensitive agricultural water management

Nutrition and health experts need to join forces with water managers at the farm household level, at the community level, and at the government level to strengthen positive transmission pathways between both rainfed and irrigated agriculture, and food and nutrition security. A recent guidance describes eight actions to increase the nutrition sensitivity of water resources management and irrigation as well as indicators for monitoring progress.

5. Increase the environmental sustainability of food systems

The water footprint of diets varies dramatically between rich and poor countries, but also by socioeconomic group within countries. More work is urgently needed on the impact of current dietary trends on environmental resources, including water. Food-based dietary guidelines should consider the environmental footprint of proposed diets, whereby government regulations and consumer awareness should be strengthened to reduce over-consumption of food, and further efforts are needed to reduce post-harvest waste and losses.

6. Explicitly address social inequities in water-nutrition linkages

Vulnerable groups need to be proactively included in the development of water services, including incorporating their needs and constraints into initial infrastructure design. For rural smallholders who most lack water and food security, irrigation design should consider multiple uses of water, such as drinking, irrigation, and livestock watering to meet women's and men's needs. While women make up a large part of the agricultural workforce, they often lack recognition and formal rights, and farmers are often considered to be 'male' in many parts of the world. Women's productive roles should be promoted, and they should be trained in irrigation and water management. It is also important to ensure that women and disadvantaged social groups (e.g. lower castes, stigmatised social groups) have equal access to credit, irrigable land, labour, and markets to buy agricultural inputs and sell their produce .

7. Improve data quality and monitoring for water-food system linkages, drawing on innovations in ICT

Better data are needed to truly understand the water footprint of diets, and devise policies that co-maximise water and food security and nutrition goals. Challenges include poor water and poor food intake data and a lack of indicators connecting the two, but improvements are emerging. Better and more data will support better water management and food systems and increase transparency in decision-making. This requires sustained investments in monitoring of a wide range of hydrological and food-related parameters worldwide. Modern Earth observation methods can support larger-scale assessment, but need to be complemented by dedicated field measurements.

REFERENCES

1. HLPE. 2015. Water for food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/av045e/av045e.pdf
2. HLPE. 2017. Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/i7846e/i7846e.pdf
3. UNSCN. 2020. Water and Nutrition. Harmonizing Actions for the United Nations Decade of Action on Nutrition and the United Nations Water Action Decade. Rome: UNSCN. https://www.unscn.org/uploads/web/news/document/Water-Paper-EN-WEB-2mar.pdf
4. Ringler, C. 2017. Investment in irrigation for global food security. IFPRI Policy Note. Washington DC: IFPRI. http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/131045/filename/131256.pdf
5. Cumming O, Arnold BF, Ban R, Clasen T, Esteves Mills J, Freeman MC, Gordon B, et al. 2019. The implications of three major new trials for the effect of water, sanitation and hygiene on childhood diarrhea and stunting: a consensus statement. BMC Med. 17(1): 173. doi: 10.1186/s12916-019-1410-x
6. Sun G, Hallema D, Asbjornsen H. 2017. Ecohydrological processes and ecosystem services in the Anthropocene: a review. Ecological Processes 6(35). https://doi.org/10.1186/s13717-017-0104-6
7. IPCC. 2018. Summary for Policymakers. In Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A et al.(eds.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty. Geneva: IPCC. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf
8. UN Environment. 2018. Progress on Water-related Ecosystems. Piloting the monitoring methodology and initial findings for SDG indicator 6.6.1. https://reliefweb.int/sites/reliefweb.int/files/resources/661-progress-on-water-related-ecosystems-2018.pdf
9. Stayer DL, Dudgeon D. 2010. Freshwater biodiversity conservation: recent progress and future chal-

lenges. Journal of the North American Benthological Society, 29(1): 344-358. https://bioone.org/journals/journal-of-the-north-american-benthological-society/volume-29/issue-1/08-171.1/Freshwater-biodiversity-conservation-recent-progress-and-future-challenges/10.1899/08-171.1.full

10. IUCN. 2019. The IUCN Red List of Threatened Species, version 2019-1. http://iucnredlist.org
11. Fricke R, Eschmeyer W, van der Laan R. 2020. Catalog of fishes: Genera, species, references. California Academy of Sciences. https://researcharchive.calacademy.org/research/ichthyology/catalog/SpeciesByFamily.asp
12. Martin-Ortega J, Ferrier R, Gordon I, Khan S. (eds.). 2015. Water Ecosystem Services: A Global Perspective (International Hydrology Series). Cambridge: Cambridge University Press
13. IEA 2016. www.eia.gov/electricity/data/browser
14. Willet J, Wetser K, Vreeburg J, Rijnaarts HHM. 2019. Review of methods to assess sustainability of industrial water use. Water Resources and Industry 21: 2212-3717. https://doi.org/10.1016/j.wri.2019.100110
15. FAO SOFA. 2020. Overcoming water challenges in agriculture. http://www.fao.org/state-of-food-agriculture/en
16. UN. 2018. Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation. New York
17. Ringler C, Zhu T., Gruber S, Treguer R, Auguste L, Addams L, Cenacchi N et al. 2016. Role of water security for agricultural and economic development – concepts and global scenarios. In Pahl-Wostl C, Bhaduri A, Gupta J (eds.), Handbook on water security. Aldershot: Edward Elgar Publishing Ltd
18. UNICEF, WHO. 2019. Progress on household drinking water, sanitation and hygiene, 2000-2017. Special focus on inequalities. New York: UNICEF, WHO. https://www.who.int/water_sanitation_health/publications/jmp-2019-full-report.pdf
19. UNICEF. Collecting water is often a colossal waste of time for women and girls. Press release. https://www.unicef.org/press-releases/unicef-collecting-water-often-colossal-waste-time-women-and-girls
20. Geere JA, Cortobius M. 2017. Who carries the weight of water? Fetching water in rural and urban areas and the implications for water security. Water Alternatives 10(2): 513-540
21. FAO. 2020
22. AUC. 2020. Framework for Irrigation Development and Agricultural Water Management in Africa. https://au.int/en/documents/20200601/framework-irrigation-development-and-agricultural-water-management-africa
23. Sadoff CW, Borgomeo E, Uhlenbrook S. 2020. Rethinking water for SDG 6, Nature Sustainability 3(5): 346-347
24. Mehta L, Oweis T, Ringler C, Schreiner B, Varghese S. 2019. Water for food security, nutrition and social justice. Routledge: London
25. Headey D, Heidkamp R, Osendarp S, Ruel M, Scott N, Black R, Bouis H. 2020. Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. Lancet 396(10250): 519-521. https://doi.org/10.1016/S0140-6736(20)31647-0
26. FAO, IFAD, UNICEF, WFP, WHO. 2020. The State of Food Security and Nutrition in the World 2020
27. UNICEF, WHO, WB. 2020. Levels and trends in child malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates. Geneva: WHO
28. NCD Risk Factor Collaboration, Bixby H, Bentham J, et al. 2019. Rising rural body-mass index is the main driver of the global obesity epidemic in adults. Nature 569, 260–264 (2019). https://doi.org/10.1038/s41586-019-1171-x
29. Perez-Escamilla R, Bermudez O, Buccini GS, Kumanyika S, Lutter CK, Monsivais P, Victora C. 2018. Nutrition disparities and the global burden of malnutrition. BMJ Jun 13;361:k2252. https://doi.org/10.1136/bmj.k2252
30. Ringler C, Choufani J, Chase C, McCartney M, Mateo-Sagasta J, Mekonnen D, Dickens C. 2018. Meeting the nutrition and water targets of the Sustainable Development Goals: achieving progress through linked interventions. Colombo: IWM. CGIAR WLE, World Bank. http://dx.doi.org/10.5337/2018.221
31. Baye K, Hirvonen K. 2020. Seasonality: a missing link in preventing undernutrition. The Lancet Child & Adolescent Health 4(1): e3
32. Madan EM, Haas JD, Menon P, Gillespie S. 2018. Seasonal variation in the proximal determinants of undernutrition during the first 1000 days of life in rural South Asia: A comprehensive review. Global Food Security 19: 11-23
33. Baye K, Choufani J, Mekonnen DK, Bryan E, Ringler C, Griffiths JK, Davies E. 2019. Irrigation and Women's Diet in Ethiopia. A Longitudinal Study. IFPRI Discussion Paper 1864.
34. Hirvonen K, Headey D. 2018. Can governments promote homestead gardening at scale? Evidence from Ethiopia. Global Food Security 19: 40-47
35. UNSCN. 2020
36. Ringler et al. 2018; UNSCN. 2020; Mehta et al. 2019; Young SE, Frongillo E, Melgar-Quinoñez H, Perez-Escamilla R, Rosinger R, Ringler C, Jamaluddine Z. 2021. Perspective: The Importance of Water Security for Ensuring Food Security,

Good Nutrition, and Well-being. Advances in Nutrition. nmab00. 3https://academic.oup.com/advances/advance-article/doi/10.1093/advances/nmab003/6144691

37. WWAP. 2018. The United Nations World Water Development Report 2018: Nature-based Solutions. Paris: UNESCO
38. WWAP. 2018
39. Yu, W., Uhlenbrook, S., Von Gnechten, R., Van der Bliek, J., 2021. Can Water Productivity Improvements Save Us from Global Water Scarcity? A White Paper. Rome: FAO
40. FAO, IFAD, UNICEF, WFP, WHO. 2020
41. Hirvonen K, Hoddinott J, Minten B, Stifel D. 2017. Children's diets, nutrition knowledge, and access to markets. World Development 95: 303-315
42. Heinke J, Lannerstad M, Gerten D, Havlík P, Herrero M, Notenbaert AMO, Hoff H. 2020. Water use in global livestock production –Opportunities and constraints for increasing water productivity. Water Resources Research. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019WR026995
43. FAO. 2020
44. Jägermeyr J. et al. 2016. Integrated crop water management might sustainably halve the global food gap. Environ. Res. Lett. 11 025002 https://iopscience.iop.org/article/10.1088/1748-9326/11/2/025002
45. World Bank. 2010. Improving Water Management in Rainfed Agriculture: Issues and Options in Water-Constrained Production Systems. World Bank Other Operational Studies 13028, The World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/13028/696130ESW0P1100gement0Rainfed0Final.pdf
46. Rosegrant MW, Ringler C, Zhu T.2009. Water for agriculture: Maintaining food security under growing scarcity. Annual Review of Environment and Resources 34: 205-223. https://doi.org/10.1146/annurev.environ.030308.090351
47. Meenakshi JV, Webb, P. 2019. Food Systems, Diets, and Nutrition: Global Trends, Challenges and Opportunities. In Agriculture & Food Systems to 2050, 215-242. https://doi.org/10.1142/9789813278356_0007
48. Lundqvist J, Malmquist L, Dias P, Barron J, Wakeyo MB 2021. Water productivity, the yield gap, and nutrition. The case of Ethiopia. FAO Land and Water Discussion Paper No. 17. Rome, FAO. http://www.fao.org/documents/card/en/c/CB3866EN
49. Asenso-Okyere K, Mekonnen DA. 2012. The Importance of ICTs in the Provision of Information for Improving Agricultural Productivity and Rural Incomes in Africa, UNDP Working Papers 2012-015. United Nations Development Programme, Regional Bureau for Africa
50. Allan JA. 1997. 'Virtual Water': A long term solution for water short Middle Eastern economies? Paper presented at the 1997 British Association Festival of Science, Roger Stevens Lecture Theatre, University of Leeds, Water and Development Session, TUE.51, 14.45. https://www.soas.ac.uk/water/publications/papers/file38347.pdf
51. WWAP. 2017
52. UNEP. 2016
53. Mateo-Sagasta J, Zadeh SM, Turral H. (eds.). 2018. More people, more food, worse water? A global review of water pollution from agriculture. Rome: FAO; Colombo: IWMI. CGIAR Research Program on Water, Land and Ecosystems (WLE). http://hdl.handle.net/10568/93452
54. Nkonya, E, Iannotti, L, Sakwa, B, Wielgosz, B. 2011. Baseline study of KickStart treadle pumps in East Africa. Washington, DC: IFPRI
55. Warner M, Kahan D, Lehel S. 2008. Market-oriented agricultural infrastructure: appraisal of public-private partnerships. Rome: FAO
56. Elsabber R. 2020. ICT for small-scale irrigation: A market study. Bonn/Eschborn: GIZ GmbH
57. van Koppen B, Smits S, del Rio CR, Thomas J. 2014. Scaling up multiple use water services: accountability in the water sector, IWMI Books, Reports H046385
58. Bryan E, Chase C, Schulte M. 2019. Nutrition-sensitive irrigation and water management. Washington, DC: World Bank. http://hdl.handle.net/10986/32309
59. Lundqvist et al. 2021
60. UNSCN. 2020
61. Mehta et al. 2020; UNSCN. 2020
62. Bryan et al. 2019; HWISE network (https://hwise-rcn.org/); Lundqvist et al. 2021
63. FAO. 2019. WaPOR, remote sensing for water productivity. https://wapor.apps.fao.org/home/1

Appendix 1. SDG 6 targets on water and sanitation

SDG 6 targets

6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all

6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations

6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally

6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity

6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate

6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes

Implementing mechanisms

6.A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies

6.B Support and strengthen the participation of local communities in improving water and sanitation management

UNITED NATIONS
FOOD SYSTEMS
SUMMIT 2021
The Scientific Group for the
UN Food System Summit
sc-fss2021.org

Food Systems Summit Report
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 6, 2021

LIVESTOCK AND SUSTAINABLE FOOD SYSTEMS: STATUS, TRENDS, AND PRIORITY ACTIONS.

by Mario Herrero, Daniel Mason-D'Croz, Philip K. Thornton, Jessica Fanzo, Jonathan Rushton, Cecile Godde, Alexandra Bellows, Adrian de Groot, Jeda Palmer, Jinfeng Chang, Hannah van Zanten, Barbara Wieland, Fabrice DeClerck, Stella Nordhagen and Margaret Gill

ABOUT THE AUTHORS

Mario Herrero, Commonwealth Scientific and Industrial Research Organisation, Australia.

Daniel Mason-D'Croz, Commonwealth Scientific and Industrial Research Organisation, Australia

Philip K. Thornton, CGIAR Research Programme on Climate Change Agriculture and Food Security, ILRI, Kenya.

Jessica Fanzo, Bloomberg School of Public Health and the Nitze School of Advanced International Studies, Johns Hopkins University, Baltimore, MD, USA.

Jonathan Rushton, Department of Livestock and One Health, Institute of Infection, Veterinary and Ecological Sciences, University of Liverpool, UK

Cecile Godde, Commonwealth Scientific and Industrial Research Organisation, Australia

Alexandra Bellows, Bloomberg School of Public Health and the Nitze School of Advanced International Studies, Johns Hopkins University, Baltimore, USA

Adrian de Groot, Impact Institute, The Netherlands.

Jeda Palmer, Commonwealth Scientific and Industrial Research Organisation, Australia

Jinfeng Chang, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China

Hannah van Zanten, Farming Systems Ecology group, Wageningen University & Research, Wageningen, the Netherlands.

Barbara Wieland, International Livestock Research Institute, Addis Ababa, Ethiopia and Institute of Virology and Immunology, University of Bern, Bern, Switzerland.

Fabrice DeClerck, Agricultural Biodiversity and Ecosystem Services, Bioversity, Norway.

Stella Nordhagen, Global Alliance for Improved Nutrition (GAIN), Switzerland.

Margaret Gill, School of Biological Science, University of Aberdeen, United Kingdom.

ABSTRACT

Livestock are a critically important component of the food system, although the sector needs a profound transformation to ensure that it contributes to a rapid transition towards sustainable food systems. This paper reviews and synthesises the evidence available on changes in demand for livestock products in the last few decades, and the multiple socio-economic roles that livestock have around the world. We also describe the nutrition, health, and environmental impacts for which the sector is responsible. We propose eight critical actions for transitioning towards a more sustainable operating space for livestock. 1) Shifts in the consumption of animal source foods (ASF), recognising that reductions in consumption will be required, especially in communities with high consumption levels, while promoting increases in consumption of vulnerable groups, including the undernourished, pregnant women and the elderly. Diet shifts alone will not produce the deep transformations required, and the following actions need to be deployed at scale at the same time. 2) Continue work towards the sustainable intensification of livestock systems, paying particular attention to animal welfare, food-feed competition, blue water use, disease transmission and perverse economic incentives. 3) Embrace the potential of circularity in livestock systems as a way of partially decoupling livestock from land. 4) Adopt practices that lead to the direct or indirect mitigation of greenhouse gases. 5) Adopt some of the vast array of novel technologies at scale and design the incentive mechanisms for their rapid deployment. 6) Diversify the protein sources available for human consumption and feed, focusing on the high-quality alternative protein sources that have low environmental impacts. 7) Tackle antimicrobial resistance effectively through a combination of technology and new regulations, particularly for the fast-growing poultry and pork sectors and for feedlot operations. 8) Implement true cost of food and true-pricing approaches to ASF consumption. The scale of the efforts on these actions will depend on the context and needs of each country or region, however, these actions will need to be deployed simultaneously and in combination to ensure that livestock contribute to sustainable food systems, leaving no-one behind.

1. INTRODUCTION

There is global consensus of the need to transform food systems to achieve critical global goals at the intersection of human and planetary well-being. The Sustainable Development Goals (SDGs) stress that to meet future needs we need to use land more sustainably, minimise negative impacts on the environment and seek for opportunities to restore lands that have lost nutrients and/or biodiversity. Simultaneously it is crucial to provide all people with access to a more nutritious diet, and hence future food systems must provide a diverse range of affordable foods to enable all people to have access to diets of high nutritional quality.

The livestock sector is an important part of these challenges, since on one hand, it is a major user of land but on the other hand, it provides food with high-quality protein and has high levels of micronutrients. Over recent decades, however, livestock production has grown rapidly in response to increasing demand, and its environmental footprint has grown to the point that the sector is now considered a major disruptor of global biogeochemical cycles, water use, biodiversity loss and others. A large reduction in the environmental footprint of the livestock sector is necessary to facilitate the continuation of conditions that have allowed humans to live on the planet and the Earth's current ecosystems to thrive.

Here, we provide a synthesis of the current understanding of the dynamics of the livestock sector in terms of use of natural resources, trade between countries and the synergies and trade-offs caused by the changing nature of the demand and supply of ASF (including milk, meat, eggs, and fish in this study). Drivers, environmental and social issues are discussed in detail, and mechanisms for enhancing the synergies are proposed. We discuss the kinds of policies, governance processes and institutions that might minimise negative interactions and maximise positive synergies. We conclude with a brief exposition of the possible implications for the international agricultural research agenda, along with eight priority actions that need to be deployed simultaneously and in combination to ensure that livestock contribute to sustainable food systems, leaving no-one behind.

Table 1 Glossary of key terms

Key Terms	Explanation
Livestock Sub-Sectors	Domesticated terrestrial animal sub-sectors that include bovine (beef and buffalo), dairy, sheep, lamb, goat, poultry, egg, and pig production.
Livestock Products	Products (food and non-food) derived from terrestrial domesticated animal sub-sectors.
Animal Source Foods	Food products derived from both terrestrial and aquatic animal sources. These include livestock food products, as well as food products derived from aquaculture, wild capture seafood, and hunting on land.
Ruminants	Terrestrial herbivores that have four stomach compartments to facilitate the digestion of fibre. Domesticated ruminants can be categorised as large (bovine, buffalo, cows) and small (sheep, goats, lamb/mutton).
Monogastric	Domesticated animals that have a single compartment stomach, this usually refers to pigs/hogs and fowls, which includes chicken, turkey, duck.
Red Meat	There are various definitions of red meat depending on geography and if the use is culinary or nutritional/dietary. In this report, we follow the WHO (2015) definition where red meat refers to mammalian meat including ruminants and pigs/hogs.
White Meat	Following nutritional/dietary definitions, in this report white meat refers to meat and meat products derived from poultry, other fowl, and seafood.
Cropland	Area dedicated to the production of food, feed, and biomass crops. This included both area for annual (e.g. cereals) and perennial crops (e.g. fruit trees).
Rangeland	Land type that can be used for livestock grazing and can vary substantially in terms of productivity, and tends to be characterised by native vegetation, but can vary in its level of intensification and management.
Pasture	Land type that is dedicated for livestock grazing. Vegetation tends to be more managed than for rangelands and is primarily grasses and other forage crops.
Feed Crop	Crop that is grown primarily to serve as a feed for animals.
Food Crop	Crop that is grown primarily for direct human consumption. Food crops can have co-products that can be used to feed animals.
Feed-Food Competition	A competition for natural resources (e.g. land) between different purposes; feed or food production.

2. BACKGROUND AND TRENDS

In recent years, the analysis of trends of the livestock sector has focused on understanding changes in demand, supply, and trade of livestock products, together with its associated intensification and expansion dynamics and environmental impacts. Most analyses of demand projections start from Delgado et al's (1999) 'Livestock Revolution' paper which built on evidence that as incomes increase and societies urbanise, per capita consumption of livestock products increases. This, together with increases in population, projected that the total demand for livestock products would grow substantially. This phenomenon, often generalised, while mostly true, hides substantial heterogeneity in terms of the types of livestock products that are likely to increase in demand and the locations of consumption growth. Below we provide clarity on the dynamics of ASF demand and supply.

2.1. Trends in animal source food demand: 1990-2015

Averaged globally, over the last 25 years, per capita food demand of all ASF increased by more than 40 kg/person/year (FAOSTAT, 2018). However, this number hides substantial variation across regions and by commodity within ASFs, with several different trends operating in opposing directions (Figure 1 and Figure S1). For example, while there was a nearly 35% increase in per capita meat demand (+11.27 kg/person/yr), and total per capita meat demand increased for all regions between 1990 and 2015, this increase is being driven by large increases in demand for poultry and pork, which saw increases of 106 and 26% respectively.

Global demand for ruminant meat (beef and mutton), however, has followed a different trajectory, with per capita demand having remained near 1990 levels (changed less than 1 kg/person/year on average globally). Within the beef trend we still see substantial variation regionally, with most regions exhibiting much bigger declines in beef demand than the global number would suggest. High-income countries have seen large declines in per capita beef demand since 1990, with Europe, United States, and Australia, with beef demand declining by 8.8, 5.8, and 6.5 kg/person/yr respectively. Latin America (excluding Brazil), South Asia, and Sub-Saharan Africa have also seen declines in per capita demand for beef. Globally, this has been balanced out by large increases in per capita demand in China and (4.6 kg/person/yr or >300%), Brazil, (11.8 kg/person per year or >40%), and Western Asia and North Africa (2.2 and 3.3 kg/person/yr or >40% and >50% respectively). Demand for mutton has followed similar regional patterns as changes in demand for beef.

There is much less diversity of trajectories in the trends for poultry. Per capita poultry demand has increased in all regions, with the only difference being the magnitude of the observed increase. The smallest increase was in Eastern Africa and the United States of America, 27 and 32% respectively in per capita demand of poultry meat. All other regions experienced per capita demand of poultry meat double. Regional pork demand trends are more variable, but resemble poultry more so than beef, with non-Muslim-majority regions generally seeing substantial increases, particularly in China, Southeast Asia, South America, and Australia.

In low- and middle-income countries, this increase in meat demand has led to substantial per capita meat demand increases driven more by large increases in demand of monogastric meats with only minimal increases in ruminant meat demand. In higher-income countries, we observe small changes (around 5%) in per capita total meat demand, masking large shifts in the makeup of meat demand, with substantial substitution of beef and mutton with pork and poultry. Global demand for dairy products is growing at a similar rate to pork, but with less regional variation with most regions seeing increasing demand for dairy products.

Fish demand per capita globally increased by more than 50%, with most regions seeing substantial increases, with the few exceptions being Eastern and Southern Africa, and the United States of America. However, the

Figure 1 Change in animal source food demand 1990-2015 (kg/person/yr). Source: Based on authors' calculations from FAOSTAT (2018). All regional definitions follow FAOSTAT definitions. Regions are inclusive of selected countries (i.e. Eastern Asia includes China), which are reported individually to highlight key trends.

	Fish, Seafood	Milk - Excluding Butter	Eggs	Meat	Bovine Meat	Mutton & Goat Meat	Pigmeat	Poultry Meat
Europe	4.5	25.3	0.6	1.8	-8.8	-1.4	0.8	10.6
Northern Africa	8.7	47.8	1.3	12.2	3.3	1.9	0.0	8.6
Western Africa	6.8	6.6	0.3	2.0	0.2	1.2	0.4	1.8
Eastern Africa	-0.9	17.3	-0.1	0.5	-0.2	0.1	0.4	0.4
Middle Africa	3.6	-5.5	0.4	8.4	-1.1	0.4	2.2	7.2
Southern Africa	-1.8	8.4	3.3	23.2	-1.2	-1.1	2.4	22.3
Eastern Asia	19.8	25.7	11.2	55.7	3.9	2.2	18.2	10.4
China	24.1	35.6	13.0	38.8	4.6	2.6	19.5	11.1
Central Asia	0.7	44.1	2.2	9.2	1.7	-0.5	2.0	5.4
Southern Asia	3.0	28.8	1.4	1.4	-0.5	-0.5	-0.2	2.8
India	2.0	35.3	1.8	0.2	-1.2	-0.1	-0.2	1.7
South-Eastern Asia	17.0	7.6	2.5	16.8	1.3	0.2	7.5	7.8
Western Asia	2.0	7.4	0.9	18.1	2.2	-1.4	0.1	25.4
Americas	0.9	12.5	2.9	19.2	-0.8	-0.2	1.5	18.6
United States of America	0.6	-4.6	1.1	5.9	-5.8	-0.3	-1.6	13.4
South America	2.0	33.4	2.7	31.2	3.8	-0.3	3.9	23.8
Brazil	4.7	57.0	1.1	44.0	11.8	-0.2	4.2	28.1
Oceania	8.2	-30.8	-0.1	7.0	-6.6	-13.5	6.5	22.4
Australia	8.1	-27.4	-1.5	6.9	-6.5	-13.9	5.2	23.0
World	7.0	18.9	3.1	11.3	-0.6	0.2	3.3	8.1

Change in kg/person/year between 1990-2015
-60.0 … 60.0

increase is mainly in farmed fish as globally captured fisheries have been stagnant or declining. Demand satisfied by aquaculture has seen 6% growth per year since 2001 with the majority of the growth in low- and middle-income countries, especially Asia (FAO, 2018).

2.2. The role of trade in meeting demand for animal source foods

The increase in consumption in some countries has outstripped supply and this has led to substantial increases in international trade in ASF in the last few decades. The value of exports globally has nearly tripled from around 59 in 1990 to almost 174 billion US$ by 2010, although total trade value represents less than 20% of global production (FAO, 2019b).

Meat in value terms has contributed nearly two-thirds of the value of exports of livestock products globally. There are only two regions, Europe and Oceania, where meat does not dominate the value of ASF international trade flows. In these two regions, the value of international dairy and eggs trade is about the same as meat. Europe and Oceania are also the largest exporters of the ASF categories accounting for almost 85% of exports of dairy and eggs. For meat, the main exporting regions at the global level are Europe (primarily pork), North and South America (beef, pork, and poultry), and Oceania (beef and mutton), which account for more than 90% of global meat exports in value terms. Nevertheless, global trade statistics do not tell the full story with respect to important regional trade patterns.

Most trade in ASFs is within the same region of origin, with most imports coming from nearby countries. For example, considering trade in meat, much of the trade of pork in Europe and mutton of East Asia and Pacific is between other countries within the region (e.g. Europe exports to Europe; Figure 2). However, while regional trade is the primary story in describing meat trade flows, there are a number of dominant trading countries that trade between continents (Figure 2; for example, intraregional bovine meat exports are dominated by the Southern Cone of South America (most of the green outside of the Latin America region row in Figure 2), particularly Brazil, Australia (in East Asian and Pacific region, which is blue), and the United States

Figure 2 Composition of 2010 regional imports of meat commodities by source of imports. The source of imports follow the colours given in the final column (i.e. imports from Europe are coloured orange, and from North America are red, etc.), so for example 91% of imports of bovine meat in Europe comes from other countries in Europe, whereas 62% of imports of bovine meat in the Former Soviet Union comes from countries in Latin America (FAO, 2019b).

of America (in North America region, which is red)). Small ruminant export is dominated by Australia and New Zealand (in East Asian and Pacific region, which is blue), which are the primary source of imports for most countries. Europe and to a lesser extent North America are the primary exporting regions supplying the bulk of traded intraregional pork. Intraregional trade in poultry is dominated by Brazil (in Latin America, which is green) and United States of America (in North America region, which is red).

Trade in ASF in volume terms is small compared to trade of feed. For example, Galloway et al. (2007) estimated that trade in meat and processed meat products accounted for less than one tenth of the volume of trade in feed grains. This is a crucial observation, as these dynamics are likely to intensify to supply feed for fuelling the demand for pork and poultry in importing regions. This comes with substantial consequences for land use and for environmental impacts, as depending on the land used for producing the feed, it could lead to substantial embedded environmental impacts in overall ASF production. A clear example is if imports of soybeans increase in Asia, this could fuel deforestation in Brazil, a primary soybean provider. In other regions, other environmental dimensions would take precedence over emissions, with the potential for substantial losses of biodiversity and disruption of water cycles in places (see Searchinger et al. (2015) for example, for Sub-Saharan Africa).

2.3. The response of production to meet the increase in demand: The monogastric “explosion”, intensification, and expansion dynamics

ASF are produced under a broad range of production conditions, across all agro-ecological zones and under different intensification and resource use efficiencies. Historically, the production trajectories have closely followed demand with increases observed in the production (Figure S2). Since the 1970s, there has been a ‘monogastric explosion’ with rates of growth in animal numbers often exceeding 4% per year, and in meat and eggs production in cases over 6-7% per year, globally. Greater availability of feed grains, rapid progress in genetics of animals with improved feed conversion ratios, coupled with short generation intervals and industrial production methods which have all been underpinned by improved control of infectious and production diseases, have made it possible to accelerate the production of eggs, poultry and pork several fold in a short space of time. Improvements in crop yields, improved feeding rations with high-quality feedstuffs, higher production efficiency, favourable prices and the involvement of the private industry in driving these dynamics played a significant role, initially in Europe, North America, and Oceania, and later in Latin America and parts of Asia (FAO, 2006).

Since 1990, global production of ASF (kg) has increased by more than 60%, an increase of almost 2% per year (FAOSTAT, 2018). Most regions exhibited substantial increases, with the largest production increases observed in Africa and Asia, which both increased their production of ASFs by more than 160% from 1990 levels, at an annual rate of more than 4% per year (double the global average). Higher-income regions, on the other hand, grew at a slower rate, with ASF production in Europe actually declining by about 15% from 1990 levels.

Across ASF commodities the fastest growth in production was for poultry meat which nearly tripled globally since 1990 (Figure 3). All regions on average saw increased production, with the global median increase in production across all countries at 125% above 1990 levels (~3.3%/year growth).

Eggs, pork, and dairy production grew at a slower pace with production increasing by 103%, 72%, and 56%, respectively. Eggs and pork similar to poultry saw increases across most regions, with the median regional/country increase of 79% and 29% respectively. In low- and middle-income regions dairy production grew at rates similar to poultry (108 and 203% in Africa and Asia respectively), but saw much smaller growth rates in developed regions, with an 18% decline in dairy production in Europe.

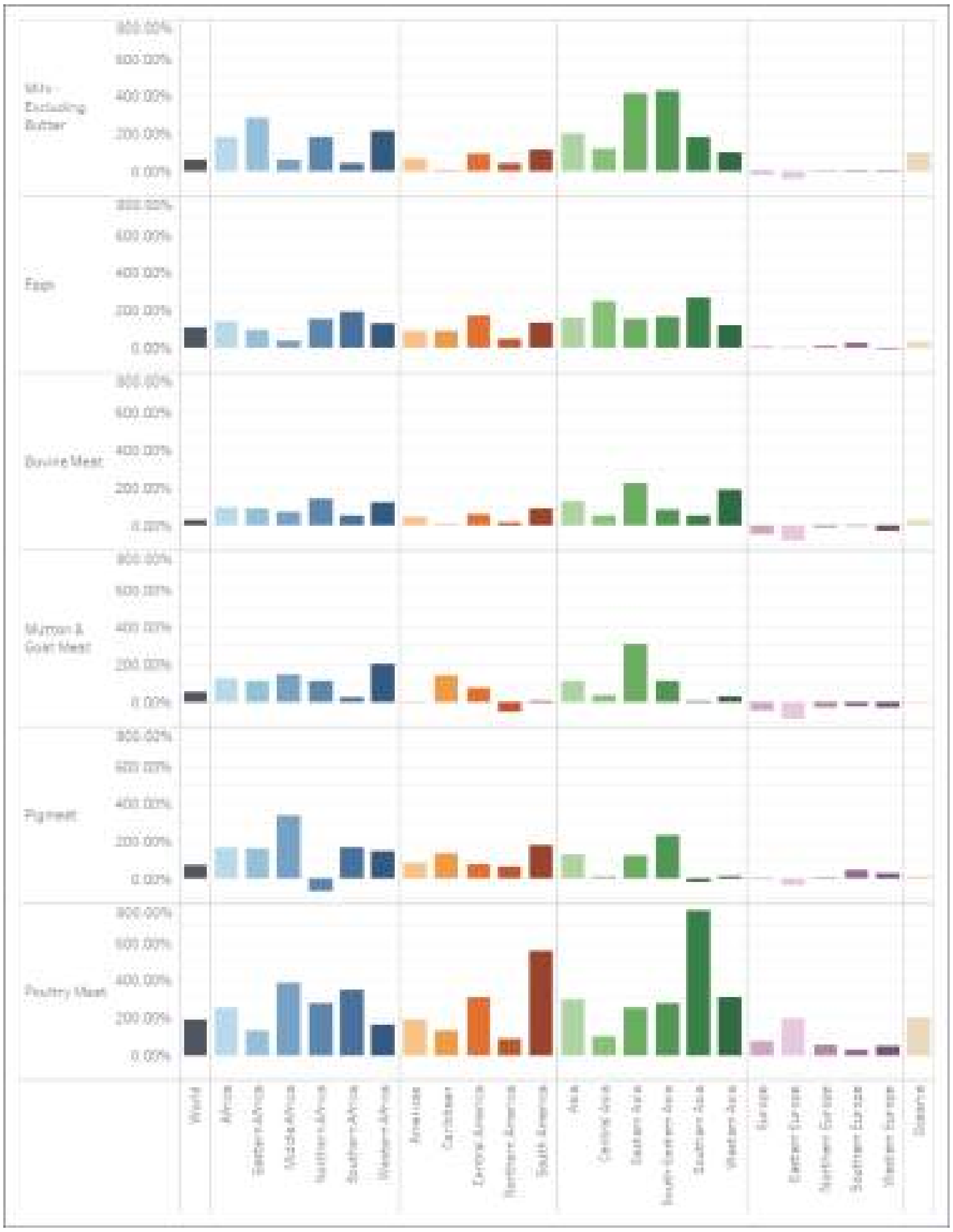
Ruminant meat production grew at a much slower pace than dairy and monogastric productions, with global production of beef and lamb increasing by 30% and 53%, respectively. Beef and lamb production globally grew about 1/4 and 1/3 the rate of poultry, respectively, since 1990. For beef, most regions saw increases in production with the exception of Europe whose production in 2015 was half their 1990 levels. Lamb production in low- and middle-income regions grew at a much faster rate than the global average, with small ruminant production increasing at rates similar to pork in Africa and Asia. However, in developed regions there were declines in production, with North America, Europe, and Oceania seeing declines in production of 58%, 49%, and 6% respectively from 1990 levels.

While increases in animal numbers and total production have occurred, substantial increases in production efficiency, often associated with intensification, have also taken place. Intensification occurred at different rates in different parts of the world and in some cases led to reductions in animal numbers. For example, the United States of America produces 60% more milk with 80% fewer cows now than in the 1940s (Capper, Cady and Bauman, 2009) through a substantial change in genetics, feeding and housing systems. Substantial intensification and also expansion of the livestock sector has occurred primarily in Latin America and Asia. This is in stark contrast with Sub-Saharan Africa, where productivity has remained stagnant for decades, with all of the growth in production due to increases in animal numbers. These general observations hide substantial heterogeneity, which we disentangle below.

2.4. Different livestock products and production systems, different dynamics

The production increases in the past few decades follow different trajectories for ruminants than for pork and poultry in smallholder or industrial operations. Between 2000 and 2011, global milk and meat production increased by 28% and 11% respectively (Figure 4). Mixed crop-livestock systems contributed to the majority of bovine milk and meat production. In 2011, mixed systems produced 505 Mt of milk and 42 Mt of meat with 608 million tropical livestock units (TLU). Grazing systems produced 45 Mt of milk and 10 Mt of meat with 192 million TLU.

Figure 3 Production trends of animal products (kg) from 1990 to 2015. Source: Based on authors' calculations from FAOSTAT (2018).



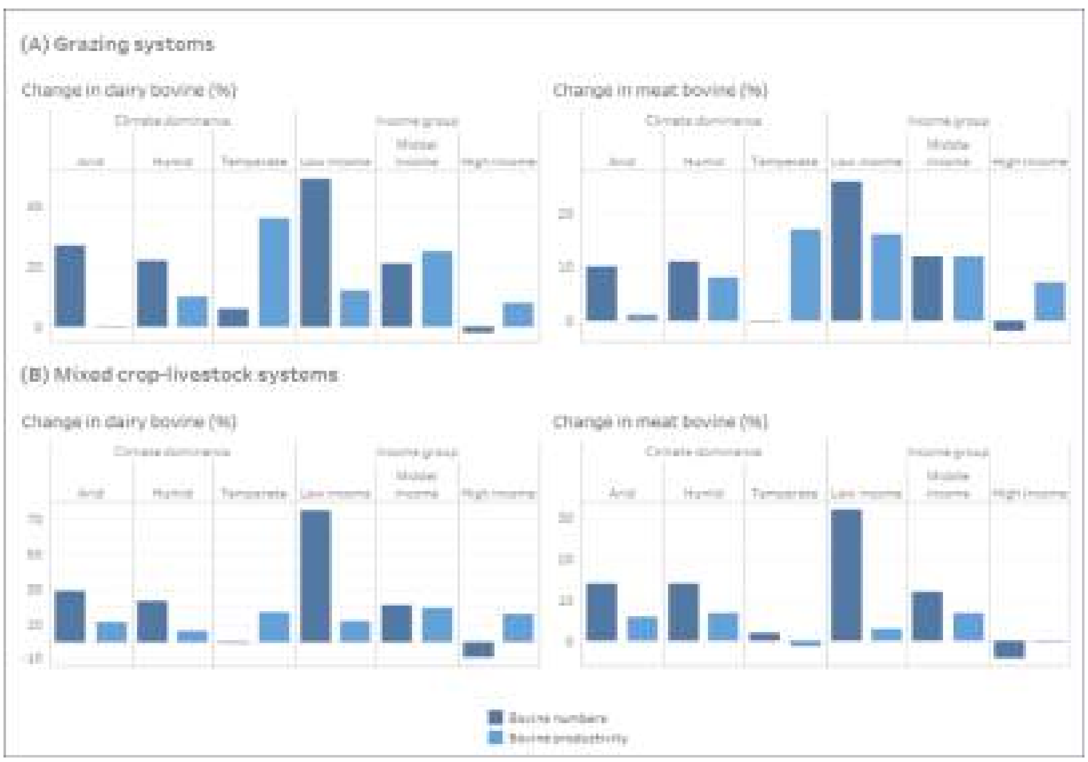
At the global level, these increases in total production were mainly driven by the increases in animal numbers (dairy: +19%, meat: +10%), followed by the increases in animal productivities (kg of livestock products/TLU/yr, milk: +9%, meat: +1%). In arid and humid regions, or in low-income countries, total production increases were mainly driven by the increases in animal numbers rather than the increases in productivity. For example, in arid grazing systems, milk productivity stagnated while dairy animal numbers rose by 27%. This reflects that the feeding systems have remained static, being reliant on animals grazing and harvesting energy from available land instead of greater utilisation of new forage crops or concentrate feeds. Similarly, improvements in animal health services in these production systems have been limited with patchy disease control, in particular over remote areas.

In contrast, in temperate regions and in high-income countries, total production increases were mainly driven by the increases in productivity rather than the increases in animal numbers. On average, high-income countries showed a decrease in total animal numbers (-4%) while maintaining modest productivity increases (under 1% per yr).

Increases in dairy productivity (28%) only outstripped the growth in animal numbers (9%) as the source of growth in dairy production between 2000-2011 in the highlands of low- and middle-income countries. This evidence of intensification is unsurprising, considering that the majority of Research and Development and extension efforts have been directed towards these smallholder, mostly mixed, dairy systems. These regions and systems have their own constraints, like increasing human population densities, shrinking farm sizes, feed deficits and soil fertility problems. These could limit the viability of dairy production in the long run in these regions (Waithaka et al., 2006; Herrero et al., 2010, 2014).

It is a concerning trend that ruminant production increases in many regions are still driven mostly by growth in animal numbers. This places additional environmental burdens on land, especially in regions with vulnerable ecosystems. A continuing trend could mean further land degradation in arid regions and increase in deforestation or land conversion in humid regions. On the other hand, efficiencies increase, as seen in e.g. broiler production systems, need to be developed with care to avoid animal welfare issues.

Figure 4 Average changes in dairy bovine milk and meat bovine productivities (kg/TLU/yr) and animal numbers in grazing systems (A) and mixed crop-livestock systems (B) by climate and income group. Period: 2000–2011. Data calculated based on productivity and animal number estimates by country, livestock system and climate type from Herrero, Havlík, et al. (2013). The climate category Arid includes semi-arid systems such as northern Australia. Grazing and mixed crop-livestock systems as defined by Robinson et al. (2011), income groups as defined by World Bank (2016). Figure adapted from Godde et al. (2018).



2.5. The role of smallholders in the production of ASF

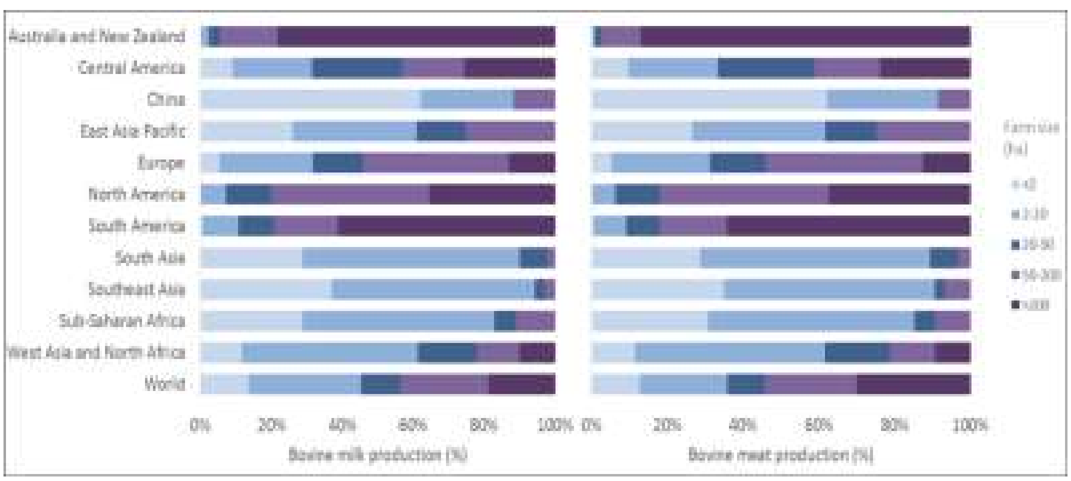
An important element in the debate of ASF production is who contributes to it, who is benefiting and whom do we need to target as primary beneficiaries of research efforts. Livestock production supports about 650 million low-income small-scale producers in lower- and middle-income countries (FAO, 2009) and approximately 117 million people work in fisheries and aquaculture (Mills et al., 2011). Livestock are responsible for 17–47% of the value of agricultural production in lower- and middle-income countries regions (Herrero, Grace, et al., 2013) and contribute income to 68% of lower- and middle-income country households (FAO, 2009), while also playing important cultural roles (Thornton, 2010; Herrero, Grace, et al., 2013). While men are often most represented in livestock production and fishing, women tend to be highly active in processing and sale of animal products (Herrero, Grace, et al., 2013). At the same time, ASF-related livelihoods do not necessarily entail high-quality jobs. For example, ASF producers and fishing communities in lower- and middle-income countries sometimes do not earn enough to eat their own production (Thow et al., 2017; Annan et al., 2018; Ravuvu et al., 2018). In high-income countries, poor working conditions in meat processing plant are well documented and, considering on-the-job mortality risk, fishing is among the deadliest livelihoods. Women in livestock value chains in particular may lack appropriate recognition and remuneration (Agarwal, 2018), and denial of women's access to shared ASF resources, such as fisheries, creates power imbalances that expose women to abuse (Fiorella et al., 2019). In improperly managed systems, animal handlers can also be exposed to, and become the vector for, zoonotic disease. Exposure to foodborne and zoonotic diseases may be particularly high in settings where workers do not have adequate access to hygiene and sanitation services. These jobs are often disproportionately held by the poorest or most vulnerable in a society—making the profile of associated risk similarly inequitable. A recent International Labour Organisation study found that a move towards more plant-rich diets could create more jobs than animal agriculture-based employment, with potential improvements in gender equality and occupational safety (Saget, Vogt-Schilb and Luu, 2020).

In the future, will the smallholders be the engine of production growth or will they be superseded by larger, more vertically integrated producers? This will likely be distinct for different livestock species and products, as the dynamics are very different for ruminant land-based systems than for monogastrics. We attempt to describe it below.

Bovine milk and meat: Globally, farms smaller than 20 ha produce 45% of bovine milk and close to 37% of bovine meat (Herrero, Philip K Thornton, et al., 2017) (Figure 5). However, important regional differences exist. Large farms (>50 ha) dominate bovine milk (>75%) and meat (>80 %) production in North America, South America, and Australia and New Zealand, which are regions with high levels of exports of these products.

Conversely, farms smaller than 20 ha produce the majority (>75%) of bovine milk and meat in China, East Asia Pacific, South Asia, Southeast Asia, Sub-Saharan Africa, and West Asia and North Africa. Very small farms (<2 ha) are of particular importance in China, where they still produce more than 60% of bovine milk and meat. These very small farms are also of importance in East Asia Pacific, South Asia, Southeast Asia,

Figure 5 The production of bovine milk and meat by farm size and region. Source: Data from (Herrero, Philip K. Thornton, et al., 2017).



and Sub-Saharan Africa, where they contribute more than 25% of bovine milk and meat production.

Bovine milk and meat production are produced across a range of farm sizes in Europe and Central America. Farms smaller than 50 ha produce more than 45% of bovine milk and meat in Europe and more than 55% in Central America.

The role of smallholders in the future is uncertain. For dairy, a sustainably intensified smallholder sector could be the engine of production growth as there are still large yield gaps in these systems. Furthermore, with demand primarily satisfied by local markets (formal and informal) and demand growing, smallholders should benefit from improved cash flow derived from growth in dairy. For intensification to occur, markets, inputs and services and increased adoption of key technological packages need to happen at a faster pace than previously anticipated (McDermott et al., 2010; Godde et al., 2018). Data from the International Farm Comparison Network has also demonstrated that there are limited signs of consolidation of land in smallholder dairy (IFCN, https://ifcndairy.org/). On the contrary, land fragmentation and feed scarcity are two of the main issues confronting these systems if they are to remain viable.

For beef, the situation is different. In the absence of a clear increase in demand per capita, and with small farm output largely dependent on increased numbers of animals, it is likely that operation size will be more of a constraint. Nevertheless, smaller scale production resulting from culled animals in diversified farming systems may continue to be economically viable even if it will be unlikely to be the main source of income or livelihoods.

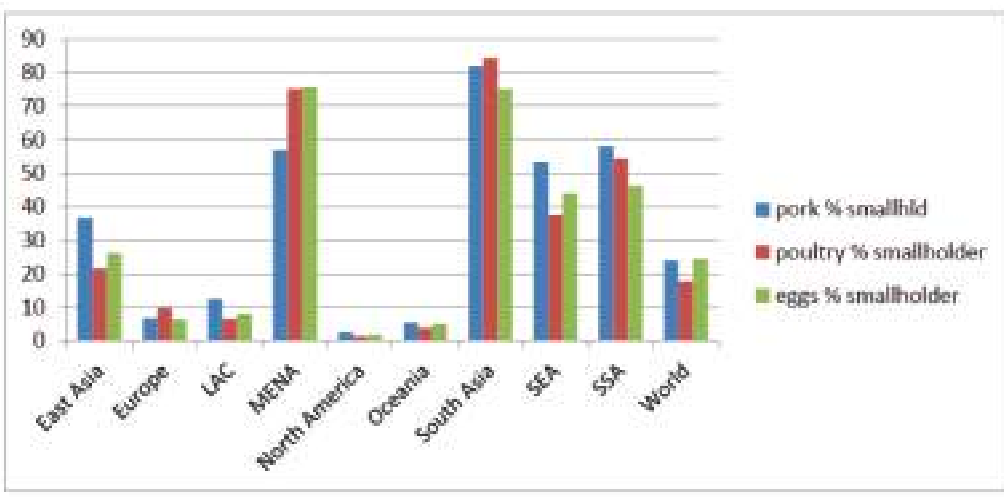
Pigs and poultry: A critical consideration for understanding the dynamics of the pork and poultry sub-sectors is to distinguish between the fast-growing industrial sector and the smallholder sector in which women are strongly represented. The contribution of smallholder systems to monogastric production based on data from Herrero, Havlík, et al. (2013), shows the importance of smallholder monogastric systems as a source of pork, poultry and eggs in several regions: notably South and Southeast Asia and Sub-Saharan Africa (Figure 6).

Gilbert et al. (2015) (Figure S3) found a negative relationship between the proportion of extensively raised chickens and pigs and the GDP per capita of different countries. According to the authors:

“Below 1,000 USD [national GDP] per capita, over 90% of chicken are raised under extensive systems and the transition from extensive to intensive production really occurs between 1,000 and 10,000 USD per capita; above which most chickens are raised in intensive systems. For pigs, the transition zone—within which pigs are raised under a mixture of extensive, semi-intensive and intensive systems—extends between 1,000 and 30,000 USD per capita. Countries with per capita GDP levels in excess of 30,000 USD tend to raise more than 95% of their pigs in intensive systems.” (Gilbert et al., 2015, p7).

Although there are large variations between countries, this suggests that as economies grow, the smallholder monogastric sector while still important in some countries, will tend to reduce in importance as income grows and conditions become more favourable for private industry to industrialise the sector. The reduction

Figure 6 The proportion of pork, poultry and eggs from smallholder systems in different global regions (Herrero, Havlík, et al., 2013).



in transaction costs and vertical integration will drive this transition as it has occurred in other regions. The question is not if but when? This transition presents a whole set of different challenges to the extensive poultry sector, as the dynamics of feed sourcing will increasingly play a key role in the sustainability of the industry, as will the impacts of increasing density in industrial systems with respect to disease dynamics (infectious diseases, antimicrobial resistance and other issues) and managing local pollution.

3. WHAT ARE THE IMPLICATIONS OF THE HISTORICAL SUPPLY AND DEMAND DYNAMICS OF ASF FOR LAND USE AND OTHER ENVIRONMENTAL METRICS?

A short historical perspective: Ramankutty et al. (2018) recently reviewed the trends in global agricultural land use. This section is largely drawn from their findings. Between 1700 and 2000, croplands expanded from ~3-4 million km^2 to ~15-18 million km^2 (Figure S4). Pastures expanded from ~500 million km^2 in 1700 to 3,100 million km^2 in 2000. Most of the cropland expansion replaced forests, while most of the pasturelands replaced grasslands, savannas, and shrublands, with some notable exceptions (e.g. the North American Prairies were replaced by croplands, while Latin American deforestation today is still mainly for grazing.

The global expansion of agriculture follows the history of human settlements and world economic order. Agricultural expansion has slowed down since the 1950s, primarily as agriculture intensified through improved crop varieties, synthetic fertilisers and management of pests and diseases. Although rapid clearing of tropical forests and savannas for agriculture continues, the current rates of clearing are relatively small compared to what happened in the temperate latitudes between 1850 and 1950. As an example, Smith et al. (2010) shows that for the period between 1990 and 2007, global cropland area increased by 3%, with the biggest regional changes occurring in Africa (6%) and Latin America (9%).

The world has around 3 billion ha of suitable land for crop production. We already use 1.5 billion ha for feeding the world, with one-third of this area used to produce feed for livestock (FAOSTAT, 2018). The remaining 1.5 billion ha are currently occupied by forests that play a fundamental role in our biogeochemical cycles and in providing a broad range of essential environmental services to humanity. These areas should be reserved, even when the short-term economic gains from conversion may be quite attractive. Any expansion of croplands into rangelands is likely to be on more marginal land, in more variable climate with subsequent lower yields than those observed on current cropland. Additionally, rangelands are important reservoirs of biodiversity and modest amounts of carbon, which suggests that their conversion would not be ideal in places like Africa (Searchinger et al., 2015). Hence, the pursuit of agricultural intensification.

Globally, total agricultural greenhouse gas emissions from have risen as a result, primarily, of increases in animal numbers and land use change. Livestock account for the majority of greenhouse gas emissions from food systems through methane from enteric fermentation and manure management, carbon dioxide from land use change and nitrous oxide from manure management (Herrero et al., 2016; Tubiello et al., 2021). However, livestock now use 62% less land and emit 46% fewer greenhouse gas emissions to produce one kilocalorie compared with 1961. These productivity gains have been observed across the livestock sector, with gains in the ruminant sector and especially dairy in Europe and North America, albeit substantially lower productivity gains than those observed for monogastrics. Nevertheless, improved livestock productivity has required an increase of 188% in the use of nitrogen fertilisers derived from fossil fuels to increase feed production (Davis et al., 2015) (Figure S5). Structural changes in the sector, driven by the monogastric explosion have been partly responsible for this trade-off, as one-third of the cropland, which uses most of the fertiliser, is now used to produce feed for livestock. Despite productivity improvements, due to increased demand, the aggregate environmental impacts of livestock have continued to grow, which will require substantial further reductions in the sector's environmental footprint.

Animal production practices, depending on type and location, can have beneficial or detrimental effects on biodiversity (Herrero et al., 2009; Barange et al., 2018). In particular, livestock-induced land use conversion is a major environmental and human rights concern in some areas (De Sy et al., 2015). Many intact ecosystems, notably carbon-dense and biodiversity-rich tropical forest biomes, have been converted to pasture and feed crops for animals (FAO and UNEP, 2020). These ecosystems are essential to climate change mitigation (Lennox et al., 2018). Intact ecosystems currently occupy half of the ice-free surface of the Earth (Dinerstein et al., 2017), and this degree of intactness has been proposed as a global limit (Newbold et al., 2016; Dinerstein et al., 2017; Leclère et al., 2018; Willett et al., 2019), implying that an urgent halt to land use conversion is needed. In extensive rangeland practices in grassland and savanna biomes, where large grazers (e.g. bison) have been lost, ruminant livestock can be an important means of biodiversity conservation and climate mitigation (Olff and Ritchie, 1998; Griscom et al., 2017).

Resource use varies widely by type of ASF and production practice. Beef production tends to be the greatest user of land and energy, followed by pork, poultry, eggs, and milk production (de Vries and de Boer, 2010). Fish, shellfish, and molluscs are generally near the low end of the range (Poore and Nemecek, 2018). Aquaculture is associated with emissions and resource use, primarily from feed production (FAO, 2013), and can also pollute water and result in habitat destruction (Barange et al., 2018; FAO, 2019a). Capture fisheries have lower environmental impacts than aquaculture on some fronts but put pressure on wild fish populations and associated ecosystems (Jackson et al., 2001; FAO, 2016, 2018; Barange et al., 2018) which have been depleted by inequitable natural resource access, and poor governance (Leroy et al., 2020). The environmental impacts of capture fisheries and aquaculture vary substantially across context, species, and production/harvesting practice (Troell, Jonell and Crona, 2019). Overall, energy use per unit protein production of fish/seafood is comparable to that of poultry and less than other livestock systems (e.g. pork, beef) (FAO, 2019a).

Resource use also varies by production system and setting. In many cases, livestock can be reared in lands of low opportunity cost, without competing with croplands or other land uses (van Zanten et al., 2018). Livestock in grazing systems may have some environmental benefits, such as conservation of grassland biodiversity, although such relationships are complex and context-specific (FAO, 2009). Animal production systems are often essential to circular production systems (Poux and Aubert, 2018). However, the intensive production of any animal, including pigs and poultry, has substantial environmental impacts, especially for surrounding communities and waterways, that must be considered (Wing and Wolf, 2000; Burkholder et al., 2007; Godfray et al., 2018).

4. THE VALUE OF FORESIGHT: WERE DELGADO AND COLLEAGUES' PROJECTIONS ACCURATE FOR 2020?

It is reasonable to review the 2020 projections made by Delgado and others towards the end of the 1990s against what is happening currently in the livestock sector.

4.1. Did the livestock revolution really happen in the last 25 years?

Globally, their projections of total meat and milk production were 304 and 772 million metric tonnes for 2020, a difference of only -12 and -5% from what current trends in FAOSTAT suggest. When we explore the projections by commodity, we observe that the projections were particularly accurate for pork, with larger deviations for beef and poultry. These deviations are offsetting, with an overestimation for beef and an underestimation of poultry production. Delgado et al. (1999) were perhaps too conservative in their assumptions of technological change and the shifts in demand for poultry, which has increased its production by a factor of three rather than doubling, as they projected. The faster transition from smallholder to industrial systems in monogastric production, as described by Gilbert et al. (2015), could have played a critical role in accelerating this change. The dynamics of this sector were simply faster than anticipated.

Table 1 Comparing global animal source food production (million metric tonnes) in Delgado et al. (1999) to FAOSTAT (2018).

	FAOSTAT			Delgado et al. (1999)	% Difference
	1990	2013	2020[a]	2020	2020
Beef	55	68	72	82	14%
Pork	69	113	125	122	-2%
Poultry	41	109	127	83	-35%
Meat	178	309	346	304	-12%
Milk	538	753	813	772	-5%

Note: [a] 2020 projection a linear regression based on FAO production values from 1990-2013

Table 3 Comparing per capita consumption of animal source food (kg/person/year) in Delgado et al. (1999) to FAOSTAT (2018)

	FAOSTAT						Delgado et al. 1999		% Difference	
	Meat			Milk			Meat	Milk	Meat	Milk
	1990	2013	2020[a]	1990	2013	2020[a]	2020	2020	2020	2020
China	25	62	73	6	33	43	60	12	-18%	-72%
India	4	4	4	53	85	92	6	125	44%	36%
World	33	43	46	77	90	95	39	85	-16%	-11%

Note: [a] 2020 projection a linear regression based on FAO production values from 1990-2013

We observe a similar story with the per capita demand projections. Overall, the projections are good with a difference of only 4 and 10 kg/person/year difference for meat and milk respectively. However, we can see that similar to the beef and poultry projections there are offsetting deviations that are masked by only looking at the global number (Table 2). Here the key deviations are for projections for China and India (Table 3). There was an underestimation on increased demand of ASFs in China, particularly for dairy products (31 kg/person/year), with a similarly larger overestimation of milk demand in India (33 kg/person/year). While the differences on the meat per capita projections for China and India are not as large as for milk, we should recognise a couple of important tendencies in these projections. First, that while Delgado et al. (1999) correctly projected a strong increase in meat consumption in China (even if they underestimated how large this growth would be), the projected increases in meat consumption in India do not appear to have materialised. Income growth in India has not translated into the expected increases in consumption across all commodities (Alexandratos and Bruinsma, 2012), perhaps in part explained by the relative slowness of the emergence of the intensive broiler sector in this country compared to east Asia.

4.2. Animal source food consumption trends: the three key storylines

Reviewing these projections highlights that the evolution of the global livestock sector over the past couple of decades can be summarised in a few storylines:

a) First, demand for poultry has been the main global driver of increased meat consumption, with per capita consumption having nearly doubled since 1990. This is a mix of changes in demand and supply.
b) Second, per capita dairy consumption in high-income regions has stayed constant since 1990, with any growth in total consumption driven by changes in population. Low- and middle-income regions have seen substantial increases in dairy consumption, with this being driven by both increases in population, and increasing per capita consumption of dairy products, with the largest increase observed in China.
c) Finally, increases in global beef demand is a story of two countries, China and Brazil, which account for nearly 93% of the 11 million metric tonne increase in global beef demand, even as globally per capita beef consumption has been declining or stagnant in most countries. The key role of China and Brazil in the global beef sector was already identified by Delgado (2003) in an update of their 1999 projections.

While the trends for overall meat have largely followed projected trends, and suggest that assumptions underlying Delgado et al. (1999) projections continue to be broadly true, recent trends do suggest that shifts towards beef may not be occurring in many countries. Conversely, in many countries, particularly in high-income countries, there has been a trend towards declining consumption of beef. This decline is especially obvious in Europe which saw a reduction of more than 10 million metric tonnes in beef demand since 1990. Nevertheless, when we exclude China and Brazil, we can see that per capita consumption in low- and middle-income countries has not increased appreciably.

Why is beef demand not growing with rising incomes like other ASF? Perhaps this can be explained by the price premium of beef vis-à-vis other meat options. Pork and poultry have been 50% and 30% cheaper than beef, respectively, between 2010-2016 according to the IMF (2017). Additionally, messages suggesting that beef consumption is less healthy than white meats have been around since the 1970s. The emergence of Bovine Spongiform Encephalopathy caused drops in demand for beef in Europe in the 1990s and disrupted trade in North America in the 2000s. More recently messaging on environmental outcomes of beef through methane production and deforestation may also be having an impact on consumer confidence.

5. Animal source foods and human nutrition and health: the need for moderation, not avoidance.

There is strong and growing evidence that global transitions to healthy diets, as defined in most national food-based dietary guidelines would lower climate and land impacts. In general, healthy plant-rich diets, including flexitarian, vegan, or vegetarian options, have lower climate and land impact than those high in ASF; their water and nutrient impacts depend on the practices used (Hallström, Carlsson-Kanyama and Börjesson, 2015; Aleksandrowicz et al., 2016; Frehner et al., 2021). Reduction in ASF, notably red meat, consumption has been shown to reduce environmental impacts (e.g. on climate, land, and biodiversity), with some studies suggesting that achieving global climate and biodiversity targets is only achievable through reduced consumption (Tilman and Clark, 2014; Leclère et al., 2018; Springmann et al., 2018; Clark et al., 2020). For example, transition to healthy plant-rich diets, including some meat, would reduce food-related emissions by nearly half, setting them on track to meet the 1.5°C climate target (Clark et al., 2020). In contrast, a global transition to increased consumption of ASF, notably red meat, is not feasible within recommended environmental limits (Springmann et al., 2018).

5.1. It is possible for healthy adults to meet their nutrient requirements from well-planned diets based solely on plant source foods

Diets that include few or no ASFs, including vegetarian and vegan diets have been shown to reduce the risk of non-communicable diseases (Tilman and Clark, 2014; Springmann et al., 2016). Diets with diverse plant sourced foods can meet protein requirements (Young and Pellett, 1994), and vegetarian diets can meet adult micronutrients needs (Walker et al., 2005). However, plant-based foods do not necessarily equal healthy foods: many highly processed foods are fully plant-based (e.g. highly processed snack foods and sugar-sweetened beverages) yet have been associated with poor health outcomes (Hu, 2013; Marlatt et al., 2016; Mozaffarian, 2016).

Controversy exists regarding dietary recommendations for some ASF and this has had a polarising effect on many scientific and food sector discussions. These foods tend to be rich in nutrients, but some specific ASF may also increase the risk of diet-related chronic diseases and have harmful impacts on the environment. Most controversial are the recommendations regarding red meat consumption, as beef production has one of the highest environmental footprints (Willett et al., 2019), but the health benefits and consequences remain contested in the literature. Consumption of red meat varies substantially by region and country-level income classification. Global intake of unprocessed red meat is estimated to be 27 g per day (26-28g per day) (Afshin et al., 2019). This is higher than the recommended optimal intake established by the Global Burden of Disease research group to reduce the risk of diet-related chronic disease (23 g/day; optimal range: 18-27 g/ day) (Afshin et al., 2019) and substantially higher than recommended intake established by the EAT Lancet commission for optimal human and planetary health (7 g/day; optimal range: 0-14 g/day) (Willett et al., 2019). Unprocessed red meat consumption was highest in Australasia and Latin America and lowest in South Asia and Sub-Saharan Africa (Afshin et al., 2019). When comparing the estimated consumption of unprocessed red meat by World Bank income classification, low-income countries have a per capita consumption of 8.2 g per day while high-income countries have a per capita consumption of 45 g per day (GBD 2017 Mortality Collaborators et al., 2018).

Differences in consumption may be due to cultural preferences, particularly in South Asia, but may also arise from differences in affordability. Interestingly, an analysis looking at the relative caloric price of foods globally found unprocessed red meat to be the most affordable ASF globally, but still at least three times higher than the price of the equivalent amount of calories from a standard basket of starchy staples (Headey and Alderman, 2019). Relative caloric price varied by income levels ranging from 2.68 in upper-middle-income countries to 3.72 in low-income countries. Regionally, unprocessed red meat was cheapest in North America and Australasia and most expensive in the Middle East and North Africa.

The United Nations Food Systems Summit Independent Science Group's working definition of a healthy diet recognises that nutrient needs to attain 'healthy' diets vary across individuals (Neufeld, Hendriks and Hugas, 2021), and ASF can be particularly important for reducing undernutrition among vulnerable groups in resource-poor settings. ASFs are a high-quality source of protein, micronutrients and bioactive factors that are important for development. Consumption of these foods may be particularly essential for young children and pregnant or lactating women as these individuals have increased nutrient requirements due to biological processes (Neumann, Harris and Rogers, 2002; Murphy and Allen, 2003; Semba et al., 2016; Beal et al., 2017). ASFs are considered complete sources of protein that provide all nine essential amino acids. In addition, ASFs are nutrient dense and have higher bioavailability of key nutrients such as iron, vitamin A, and zinc compared to plant source foods (Murphy and Allen, 2003). Regarding undernutrition, most studies have assessed the role of ASFs in linear growth for children under the age of five and micronutrient deficiencies in both women and children. Recent systematic reviews have identified limited evidence regarding the association between consumption of ASF and linear growth during early childhood. Both reviews concluded that substantial heterogeneity in definitions of ASFs might have led to inconsistent results (Eaton et al., 2019; Shapiro et al., 2019). On the other hand, a cross-sectional analysis of Demographic Health Surveys found a strong association between ASF consumption and stunting (with ASF consumption reducing stunting), and consumption of multiple ASF sources had an additive effect on the relationship (Headey, Hirvonen and Hoddinott, 2018). This analysis distinguished between dairy, egg, meat, and fish as types of ASFs, but authors were unable to look at associations between stunting and red meat specifically. In addition, another study found a strong correlation of ASF intake and reductions in stunting in Nepal and Uganda, with dairy consumption having the strongest correlation (Zaharia et al., 2021).

The association between red meat consumption and diet-related chronic diseases is highly debated among scientists. Evidence is clear that consumption of processed red meats is detrimental to health, but the relationship between unprocessed red meat and health needs further research. Evidence from epidemiological cohort studies has found positive associations between unprocessed red meat consumption and type-2 diabetes, cardiovascular disease, and cancer (Pan et al., 2011; Mozaffarian, 2016; Qian et al., 2020). In 2015, the International Agency for Research on Cancer classified processed meat as a group 1 carcinogen and unprocessed red meat as a probable carcinogen (IARC, 2015). On the other hand, in 2019, a systematic review found "low certainty" of evidence regarding red meat and poor health outcomes because of the limited data from randomised control trials and heterogeneity in effect size of estimates between studies (Johnston et al., 2019).

In summary, populations consuming high amounts of red meat, particularly in processed forms, would benefit from reduced consumption to improve health and sustainability. This mostly applies to consumers in higher-income countries but also, to a growing number in lower- and middle-income countries, where the burden of diet-related non-communicable diseases is growing rapidly. For those vulnerable to undernutrition (whether in lower- and middle-income countries or higher-income countries), the nutrient contribution of minimally processed ASF may be beneficial to reduce risk of micronutrient deficiency and promote growth (Murphy and Allen, 2003).

6. ESSENTIAL ACTIONS FOR ENSURING LIVESTOCK'S CONTRIBUTION TO SUSTAINABLE FOOD SYSTEMS

This section examines some alternative or additional actions that would need to take place for livestock to contribute to sustainable food systems, while addressing critical aspects of social equity, poverty and other social goals.

6.1. Achieve a balance in the consumption of animal source foods that improves health and nutrition for all, and that helps reduce the environmental pressures of livestock production.

As discussed in section 5, this will require different actions depending on the context, including:

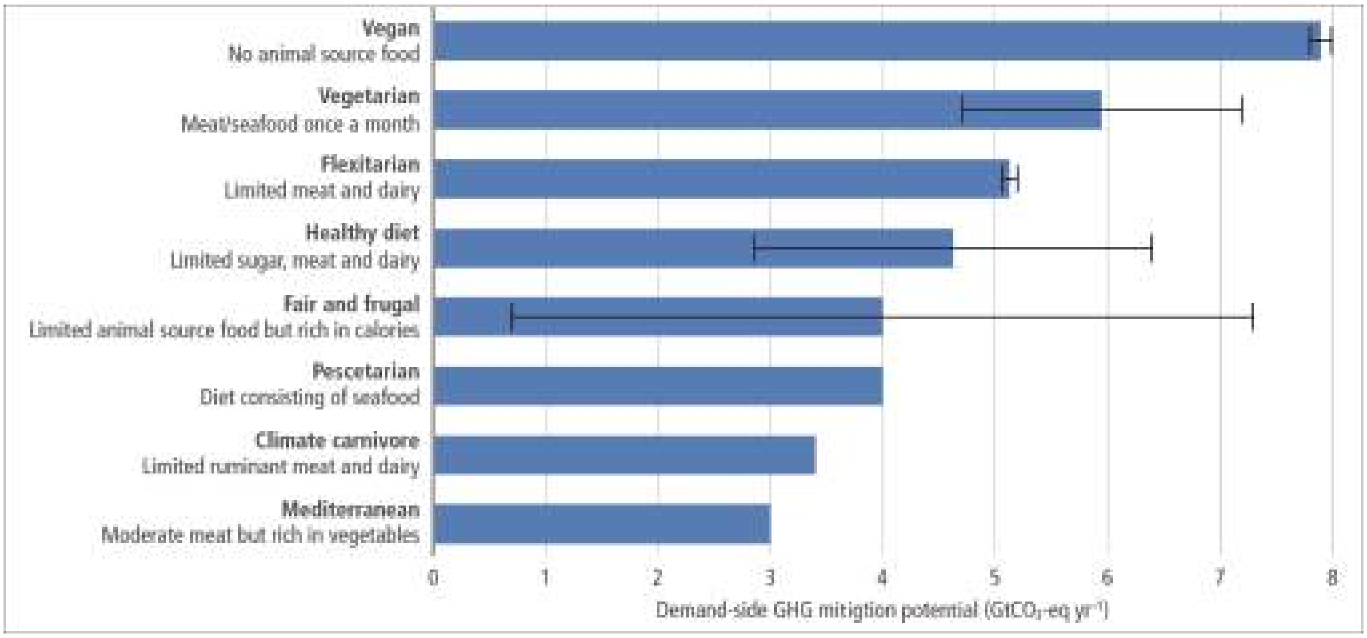
- Consumption of ASF at a level appropriate to meet nutritional needs.
- A reduction in consumption of red and processed meat for populations with high risks of diet-related non-communicable diseases or in the context of an unbalanced diet.
- Enable increased consumption by nutritionally vulnerable populations needing higher levels of nutrients including pregnant women, the elderly, children and undernourished populations, particularly those in lower- and middle-income countries.

These changes will require an integrated approach that includes a strong regulatory and fiscal framework and enabling environment in combination with awareness raising and education to encourage behavioural changes among consumers, producers, and industry including new norms and standards.

6.1.1. What sort of environmental gains could we expect from changes in consumption?

Several studies have quantified the potential environmental gains of changing dietary patterns. This area of work started from the need to quantify greenhouse

Figure 7 The technical greenhouse gas mitigation potential of changing diets according to a range of scenarios examined in the literature (Mbow et al., 2019).



gas mitigation potentials of changing diets (Stehfest et al., 2009), and has been expanded considerably to include health impacts and several additional environmental metrics (Tilman and Clark, 2014; Leclère et al., 2018; Springmann et al., 2018; Willett et al., 2019). As an example, Figure 7 summarises the technical mitigation potential of changing diets.

The features of these studies show that:

1. The upper bound of the technical mitigation potential of demand-side options is about 7.8 Gt CO2-eq per year (no consumption of animal products scenario) (Stehfest et al., 2009).
2. Many dietary scenario variants have been tested. Key variants include target kilocalorie levels (i.e. 2500 kcal per capita per day), notions of healthy diets, swaps between animal products (red vs. white meat) and/or vegetables, and stylised diets (Mediterranean, flexitarian, etc.). All fit roughly between the current emissions and the Stehfest et al. (2009) upper bound.
3. The main impact of reducing the consumption of ASFs is to reduce the land footprint of livestock. This land sparing effect, coupled with alternative uses of the land (i.e. negative emissions technologies), leads to a large mitigation potential. Many of the other environmental impacts are also associated with the land sparing effect (i.e. biodiversity, Leclère et al., 2018).
4. The largest technical potential comes from reductions in ruminant meat consumption (most inefficient sub-sector), as most scenarios try to trigger land sparing (reduction of carbon dioxide emissions) as the key mechanism for reducing emissions.
5. Reductions in livestock product consumption, especially red meats, could have both environmental and health benefits (Tilman and Clark, 2014; Willett et al., 2019).
6. Full vegan diets could meet calorie and protein requirements but can also be deficient in key nutrients (vitamin B12, folate, Zinc), a concern for vulnerable groups, in particular those without access dietary supplements. Therefore, diets with some level of animal products may be necessary.
7. The economic mitigation potential of changing diets is not known. This is a crucial research area, together with mechanisms for eliciting behavioural changes.
8. Most scenarios so far have taken kilocalories as the currency for changing diets, none have dealt with protein or micronutrients, which from a livestock and a healthy diet perspective seems like a necessary step.
9. Very few key examples of legislation and policy-induced shifts in consumption exist. There are some examples that have been shown to promote increases in consumption of fruits and vegetables (Garnett et al., 2015).

10. The social and economic costs of reduced demand for ASFs are unknown. Notably there is little information on impacts on farmers income, employment, alternative labour markets, reductions in agricultural GDP, etc.
11. Methodological advances are needed for eliciting simultaneously the environmental, health and socio-economic impacts of reduced consumption.

These studies, while important, have only told part of the story and have opened important research areas to complete the picture. These studies tend to lack information on the power of the private sector to adopt and adapt technologies and make them attractive to consumers. Many food companies are now seeing an advantage to plant-based alternatives to meat and milk as they may become more profitable as the technologies mature. In addition, all scenarios have modelled the impact of given diets, and have not explored how the diets would be achieved, which makes the ex-ante evaluation of policies to shift demand patterns difficult, if not impossible. From a technological change perspective, most of these studies use fixed environmental impacts per kg of product and since they do not change through time they do not take into account the potential for food systems redesigns.

Attached to livestock production is an enormous amount of wealth generation, employment, value chains and famers livelihoods. Impacts on these are seldomly studied and they are crucial to create convincing policy cases for a contraction of livestock product demand. Global studies that have started to include some of these critical feedbacks are only now starting to emerge (i.e. Mason-D'Croz et al., 2020).

From a nutritional perspective, there are also important improvements to be made. All scenarios so far have used kilocalories as the currency. However, livestock's contribution to healthy diets are not so much about their kilocalories as their micronutrients and protein. It is essential to include these in future research. Diets in these scenarios are also too 'globalised', and more realistic, and culturally sensitive regional variants will need to be examined. The differentiated impacts of ASF consumption and production across population cohorts, will require that future analysis begin to better recognise the heterogeneity of populations (rural/urban, under or over nourished, gender, age, or by age groups), if they are to provide necessary information to improve the targeting of future food policies.

Changes in consumption will not be enough to achieve the transformation required to achieve healthy diets from sustainable food systems. The next suite of ancillary actions will be required in tandem with consumption changes.

6.2. Sustainably intensify livestock systems

Sustainable intensification has been high on the agenda for some time (Garnett et al., 2013). In livestock systems, successful examples exist but all have been associated with the availability of inputs (high-quality feeds, fertilisers, etc.), services (veterinarians, extension) and in many cases, the development of markets and their associated value chains (McDermott et al., 2010), as these are key incentives for systems to intensify (Herrero et al., 2010; McDermott et al., 2010). Currently, adoption of better feeding practices, such as improved forages, have shown low adoption rates. For example, Thornton and Herrero (2010) found 10-25% adoption rates of dual-purpose crops, agroforestry practices and improved pastures by farmers in selected low- and middle-income regions, over a 10-15-year horizon. Increasing adoption rates will require significant public and private investment and institutional change to be able to increase farmer adoption and reduce adoption lag times.

Efforts at sustainable intensification can have negative unintended consequences, which will need to be addressed through appropriate regulation and policy action to ensure sought after environmental benefits are realised. The concept of sustainable intensification sounds to many as a win-win strategy to increase resource use efficiencies, but it is essential that it also improves animal welfare (Garnett et al., 2013), and does not contribute to increased food-feed competition (van Zanten et al., 2018). To improve human and planetary health it is crucial to assess to what extent sustainable intensification strategies could bring us closer to achieving the SDGs.

From a livestock perspective, most well managed intensification practices in the past have led also to improved systems profitability and leading to increased production (i.e. pasture intensification and supplementation in the tropics has substantially improved milk and meat production). As a result, farmers have often increased the size of their operation (more animals, more land use changes) to increase even further the economic returns. This growth in turn has led to increased environmental problems (more deforestation, increased greenhouse gas emissions, more land degradation, more temperature forcing). A critical challenge ahead is how to regulate intensification so that it is truly sustainable and equitable, operates within limits of production growth, protects biodiversity and other ecosystems services, and attains net or near net reductions in the use of resources. This is of particular importance, as having fewer animals, but of higher productivity, is essential to maximise the environmental benefits (i.e. reductions in greenhouse gas emissions and land use) of productivity growth in livestock systems (Thornton and Herrero, 2010). This would imply reversing the observed trend of increased ruminant numbers as the main source of production growth in low- and middle-income regions towards productivity increases.

The degree of competitiveness of smallholders against imports from countries that can produce vast amounts of animal products, at lower production costs, will be a crucial factor to determine the success of livestock farmers in the low- and middle-income countries, especially as the volume of traded livestock products increase. Formal and informal markets will need to ensure the supply of cheaper, locally produced, safe livestock products to adequately compete. This implies a substantial reduction in transaction costs for the provision of inputs, increased resource use efficiencies, and more responsive, innovative and supporting institutions for the livestock sector in low- and middle-income countries (FAO, 2009). Hence, investment in low- and middle-income efficient value chains (including market development, service provision, adequate institutional support, etc.) should be high in the development agenda.

6.3. Implement practices that lead to greenhouse gas mitigation co-benefits explicitly, or indirectly

Mitigating greenhouse gases from livestock systems is more feasible in some contexts than in others, and this largely depends on the livelihoods objectives of livestock farmers (Herrero et al., 2016). Nonetheless, many practices that improve productivity or the production system as a whole, can lead to direct and indirect greenhouse gas mitigation co-benefits. These should be pursued.

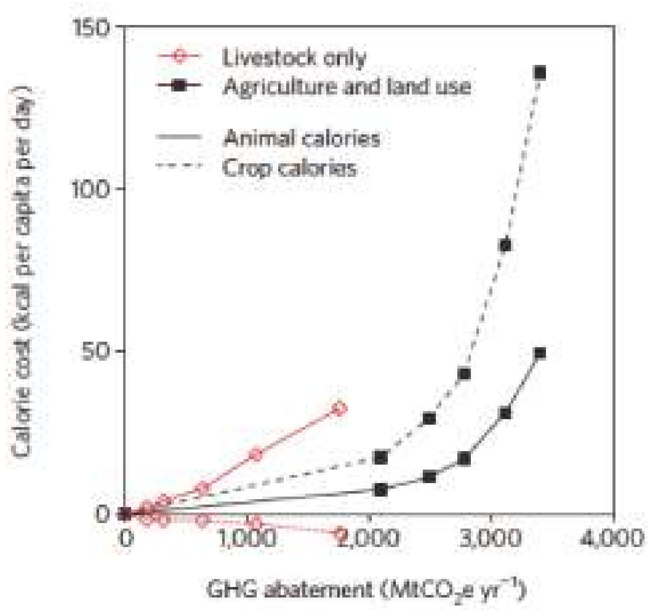
The supply side options for mitigating greenhouse gases in the livestock sector have been the subject of the recent reviews (Smith et al., 2007, 2014; Hristov et al., 2013; Herrero et al., 2016; Roe et al., 2019). These options look to:

- Reduce enteric methane of ruminants
- Reduce nitrous oxide through manure management of both ruminants and monogastrics
- Implement best animal husbandry and management practices (all), which would have an effect on major greenhouse gases (carbon dioxide, methane and nitrous oxide)
- Directly sequester carbon from pastures (ruminants)
- Generally, improve land use practices that also help enhancing soil carbon sequestration.

Excluding land use practices, Herrero et al. (2016) found that these options have a technical mitigation potential of 2.4 GtCO2eq/yr. However, they also found that the economic feasibility of these practices is low (10-15% of the technical potential, or less than 0.4 GtCO2eq/yr).

The largest mitigation opportunities for the livestock sector occur when livestock are considered holistically as part of the agriculture, forestry and land use sectors (Havlík et al., 2014, Figure 8). This is what gives the flexibility to the ruminant sector to be able to relocate production to regions with higher production efficiencies, and to spare land for the land use sector to engage in negative emissions technologies to mitigate the highest volumes of greenhouse gases. Importantly, this can be done at low consumption costs in many cases (Havlík et al., 2014). A prerequisite to trigger the land sparing effect is also to substitute the growth in production from animal numbers for increases in productivity and reducing animal numbers, which will not happen unless we develop the appropriate incentives systems that prevent rebound from the intensification strategies, which are often profitable (Thornton and Herrero, 2010).

Figure 8 Total calorie abatement costs for livestock and agriculture and land use at different carbon prices ($5 to $100 / tonCO2) (Havlík et al., 2014).

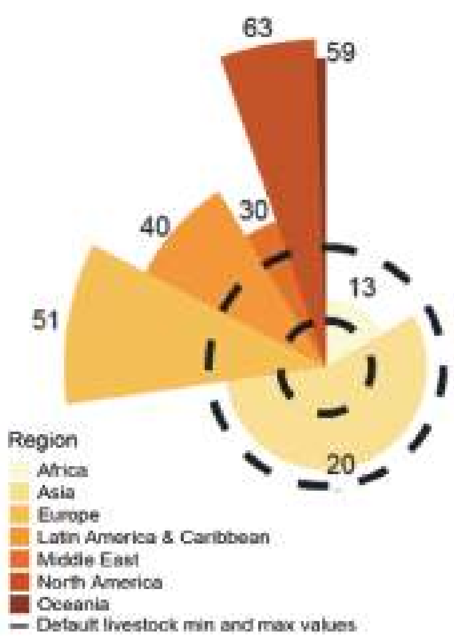


6.4. Embrace the potential for circularity in the livestock sector

Van Zanten et al. (2018) recently summarised studies focusing on circularity in the livestock sector and found that at the global level, if ruminant livestock were raised only in areas with no opportunity costs with respect to growing crops, ruminants would be able to supply 3-7 g of protein per capita per day. This protein would come mostly from ruminant meat and milk grown in rather extensive conditions, where climate variability or agroecology would preclude crop production. They also found that if by-products and other leftover streams from waste could be recycled and incorporated in rations for monogastrics, then 13-20 g protein per capita per day could be produced and fulfil vitamin B12 and half of the daily calcium requirements in a fully decoupled way from land use. This is of significance as a human roughly needs 50 g protein per capita per day. This would mean that a global circular livestock system could provide 40% of the human protein needs with substantially lower environmental impacts and no direct land needed for feed production.

Van Zanten et al. (2018) showed the consumption of ASF in different regions of the world against the range of protein produced through circular livestock systems globally (Figure 9). Under such a system, we could keep within the circularity bounds: Africa and Asia could maintain the current levels of ASF consumption and even increase them, however, all other regions would require reductions in ASF consumption. This adds additional nuance to often polarised debate on sustainable ASF production and consumption, and should be the subject of future research.

Figure 9 Animal source food consumption by region (g protein per capita per day) against the lower (13 g per capita per day) and upper (20 g per capita per day) bounds of ASF supply through circular livestock systems (van Zanten et al., 2018).



6.5. Adopt technological innovations in livestock production at scale

Technological change in food systems is occurring very rapidly and is the subject of considerable research (see Herrero et al., 2020, 2021 for reviews). Innovation in feed production, digital technologies, robotics, genetics and many other fields are shaping agriculture considerably. Several of the emerging options have the potential to disrupt the livestock sector and contribute to positive changes in the next decade if appropriate regulatory frameworks and social acceptability can be achieved. Below we present a few examples of these and how they could increase the sustainability of the production methods in the livestock sector.

Industrial feed production pathways: Engineers have created methods to produce high-quality microbial protein (85% protein) by fermenting sewage with a source of carbon dioxide and energy. After cleaning, drying and pasteurising the material, this is transformed into a powder that can be used as an ingredient by the feed industry to replace protein sources like soybeans. Pikaar et al. (2018) recently found that by 2050, microbial protein can replace, depending on socio-economic development and microbial protein production pathways, between 10−19% of conventional crop-based animal feed protein demand. As a result, global cropland area, global nitrogen losses from croplands and agricultural greenhouse gas emissions could be reduced by 6% (0−13%), 8% (3− 8%), and 7% (6− 9%), respectively. These are encouraging results, considering that this is one of many potential technologies, and could contribute towards reducing the environmental impacts of burgeoning monogastric demand. This technology is also in line with an extended circular concept for the food system even as the next example.

Superfeeds: Superfeeds, like algae or grasses with high oil content are currently the subject of significant research. Walsh et al. (2015) studied the technical potential of algae systems as feedstock and showed that if production were to be implemented in large scale in all regions where there is potential to grow it, it could replace 2 billion ha of grasslands and croplands. This could lead to substantial emissions reductions through avoided land use change and land sparing, which could be used for afforestation and rewilding. While they only demonstrated the technical potential (economically this is still not feasible right now), it shows the boundaries of what could be possible when the right sets of incentives are developed. Similarly, CSIRO have been developing grass varieties with 30% of oil in them, mostly for biofuels (Vanhercke et al., 2017). However, they could potentially be fed to livestock. This could disrupt the way we think about forage improvement in the future, and if deployed in suitable areas it could change how ruminant livestock are raised. Productivity could increase several folds if the energy density of the diets were to be dramatically increased. If coupled with reductions in animal numbers, this could also lead to substantial mitigation effects. A challenge with this approach includes the possibility that these new grasses could be more prone to pest attacks. Considerable research is still needed in this area.

Novel anti-methanogenic compounds: Significant progress has occurred in the last 4 years in identifying plants and/or compounds that could substantially reduce methanogenesis in ruminants. Two notable examples, already on the market but with increasing potential for commercialisation are Asparogopsis taxiformis algae, developed by CSIRO, which has shown reductions of 60-80% in methane production in cattle when fed at rates of 2-3 g per day (CSIRO, 2021). This would be useful for confined animals, like in smallholder systems, or in feedlots or dairy operations. The other compound is 3-nitrooxypropanol (3-NOP), which can decrease methane by up to 40% when incorporated in diets for ruminants (Hristov et al., 2015). These two examples could potentially reduce methane from enteric fermentation, although these additives would have no direct effect on the land footprint of ruminants and the carbon dioxide and nitrous oxide emissions from ruminants will remain.

Virtual fencing: Virtual fencing comprises collaring animals with GPS devices with the coordinates of the areas they graze in (Campbell et al., 2018). If the animals trespass the designated grazing areas, they receive a negative stimulus, and through training they learn to keep in the designated areas. This could contribute to improved grassland management and pasture restoration, and reduce the cost of extensive systems by reducing the need for fencing and labour to manage herd movement. Some of these grazing management systems could also lead to higher productivity and to improved emissions intensities.

Robotics/digital agriculture/sensors: Several start-up companies are deploying digital technologies in the livestock sector with great success across a broad range of domains. These include monitoring of welfare conditions for pigs and poultry, disease surveillance, precision feeding, monitoring of physiological status and others (https://animalagtech.com/start-ups-transforming-the-livestock-industry/).

6.6. Diversity protein production with high-quality alternative protein sources with lower environmental impacts

Diversifying the protein sources for human consumption and animal feed will be required as a critical action for transitioning towards a more sustainable food system. Meat and dairy analogues have a long history, with tofu, seitan, and almond and soy milk consumed for hundreds if not thousands of years (Shurtleff and Aoyagi, 2014; Kemper, 2018). 'Veggie burgers' as we currently know them were introduced to mass markets in the 1970s (Smith, 2014). Nevertheless, as a new generation of protein alternatives begin to enter the market, the attention being given to alternative protein sources for human food and livestock feed is burgeoning. These next generation technologies include a range of novel plant-based meat alternatives (e.g. Beyond Burger, Impossible Meats, etc.), insect-based proteins, and cultured meat and dairy products, all of which may displace conventional ASFs as well as first- and second-generation vegan and vegetarian alternatives. Those alternative protein sources have the potential to reduce the environmental impact (Parodi et al., 2018).

The size of plant-based meat market was between $4-5 billion in 2018, or about 10% of the meat market, with rapid growth observed over recent years (Gerhardt et al., 2020). Non-dairy milk alternatives reached $21 billion by 2015, doubling from the levels in 2009 (Bridges, 2018) and account for around 13% of the milk market (Sheikh, 2019). Substantial investment in alternative proteins has been documented with the sector receiving nearly $3.1 billion in investments in 2020, a nearly 4-fold increase from 2018 (Keerie, 2021). Alternative proteins have seen rapid growth in the last decade, and with increasing investments, some projections suggest they could capture substantial future market share, with novel plant-based alternatives (25%) and cultured meats (35%) potentially capturing the majority of meat expenditure by 2040 (Gerhardt et al., 2020). Such technology may be highly disruptive to existing value chains and lead to substantial reductions in land use for pastures and crop-based animal feeds (Burton, 2019). The resultant impacts on greenhouse gas emissions depend on the meat being substituted and the trade-off between industrial energy consumption and agricultural land requirements (Mattick et al., 2015; Alexander et al., 2017; Rubio, Xiang and Kaplan, 2020; Santo et al., 2020).

Livestock feeds can use a variety of sources of protein, such as insect protein. Insects are generally rich in protein and can be a substantial source of vitamins and minerals. Black soldier fly, yellow mealworm and the common housefly have been identified for potential use in feed products in the European Union, for example (Henchion et al., 2017). Replacing land-based crops in livestock diets with some proportion of insect-derived protein may reduce the greenhouse gas emissions associated with livestock production, although these and other potential effects have not yet been quantified (Parodi et al., 2018). Other sources are high-protein woody plants such as paper mulberry (Du et al., 2021) and algae, including seaweed. While microalgae and cyanobacteria are mainly sold as a dietary supplement in the form of tablets and health drinks for human consumption, they are also used as a feed additive for livestock and aquaculture. Nutritionally, they are comparable to vegetable proteins. The potential for cultivated seaweed as a feed supplement may be even greater, and some red and green seaweeds are rich in highly digestible protein. Novel protein sources may have considerable potential for sustainably delivering protein for food and feed alike, although their nutritional, environmental, technological and socio-economic impacts at scale need to be researched and evaluated further.

6.7. Tackle antimicrobial resistance effectively

Livestock and aquatic species are a major user of antimicrobials and antibiotics (Van Boeckel et al., 2015). This has raised concerns that poor antimicrobial use in livestock production will lead to increased antimicrobial resistance that will affect human health and undermine antimicrobial treatments for humans. These concerns have led to legislation changes on the use of antimicrobials for growth promotion in livestock, starting first in Europe in 2006 and now widespread and accepted at a global level.

There have been efforts to document the levels of antimicrobial use across livestock species and production systems, and identify the main health problems that stimulate their use (Wieland et al., 2019; Gemeda et al., 2020). In some countries, this is also being linked to surveillance of pathogens and antimicrobial resistance profiles (FAO, OIE and WHO, 2010), yet knowledge gaps remain. There is uncertainty about how changes in antimicrobial use will impact on livestock production, however, studies from Europe and Southeast Asia indicate that reductions and improved management can have a neutral impact on productivity (Raasch et al., 2020; Phu et al., 2021).

The antimicrobial use/antimicrobial resistance complex in livestock and aquatic species has multiple dimensions and multiple outcomes in terms of food production, pathogen management, antimicrobial resistance change and consequent environmental and human health impacts. Interpretation of antimicrobial resistance findings requires a better understanding of the inputs to the system, antimicrobial use, and residues of antimicrobials in the environment and animal products. Recognising the complexity of the system, a study in the aquaculture sector in Vietnam on antimicrobial resistance risks showed the value of a systems thinking approach to obtain desired objectives (Brunton et al., 2019). There is a need for more research on human behaviour across the livestock and farmed aquatic food systems, including the drivers and motivators of antimicrobials use and the role of human behaviour in exposure to antimicrobial resistance risks.

Antimicrobial use occurs within the context of regulations and enforcement, which includes legislation and policing as a framework with actions guided by a combination of private standards, market access, and social and cultural norms. In addition to intergovernmental standards, there are powerful examples of the use of private standards to manage antimicrobials in the food system. Countries with high levels of antimicrobial use in terrestrial and aquatic farmed species can be successful in exporting products with no detectable residues. Understanding the institutional environment within which antimicrobial use occurs and the relative importance of public policy, private company strategy and individual incentives will be critical to achieving sustainable antimicrobial use.

The antimicrobial use/antimicrobial resistance complex is context-specific. Achieving sustainable antimicrobial use will likely require substantial education and training of multiple actors within the ASF system, as well as the development of an effective surveillance system. The process should consider (1) the importance of understanding flows through the livestock and aquatic systems with a focus on antimicrobials, pathogens and antimicrobial resistance, (2) surveillance that uses technology appropriate for the context and that is cost-effective and sustainable, (3) interventions that can manage immediate problems with a focus on hygiene and waste water management, (4) effective communication of surveillance and intervention needs to government, the private sector and wider society, and (5) ensuring that mechanisms are in place for best practice in antimicrobial use through improved antimicrobials stewardship.

6.8. Implement true cost of food and true-pricing approaches to animal source food consumption

Transitioning to a sustainable food system will entail reducing the environmental, social and health costs of food, while increasing the affordability of food and improving the conditions of people who depend on food producing systems for their livelihoods. For livestock systems this requires balancing many trade-offs and simultaneously meeting various SDGs. Finding pathways that can benefit multiple goals is challenging, as the size and value of the various costs and benefits can be hidden. Typically, environmental, social and health costs and benefits are externalised: not included in prices (Baker et al., 2020). As a result, sustainable and healthy food is typically more expensive to consumers and less profitable to businesses than unsustainable or unhealthy food (Gemmill-Herren, Baker and Daniels, 2021). This creates a major barrier for transitions to sustainable livestock systems.

One solution is true pricing or true cost accounting, the systemic measurement and valuation of positive and negative environmental, social, health and economic costs and benefits (Baker et al., 2020; Gemmill-Herren, Baker and Daniels, 2021). True pricing can create the right incentives to enable livestock food chains to reduce their environmental costs and provide healthy food. By also considering food security, affordability and a living income for subsistence farmers, it also weighs the interests of the most vulnerable people in the food system. Given the large variation in the externalities of livestock systems, true pricing can incentivise the most efficient food systems when externalities are considered (Baltussen et al., 2016). At a global scale, it can help balance supply and demand for animal protein, shift consumption towards the most sustainable and healthy animal-based protein sources and shift production to those production types and locations where animals can be held with the lowest effects on the environment.

True cost accounting analyses of livestock have shown that the annual environmental costs of livestock systems are substantial and Baltussen et al. (2016) estimates it over 1 trillion USD per year. At the same time, there is substantial variation between types of animal food, regions, and production system. Natural capital costs increase from poultry on the low end to milk and beef on the high end on average. However, within every species there is substantial variation of natural capital costs due to heterogenous production practices. Subsistence systems can be particularly efficient: these systems supply food to the most vulnerable populations, are well adapted to local constraints and have a low or even positive impact on biodiversity (Baltussen et al., 2016, 2019).

7. CONCLUDING REMARKS AND RECOMMENDATIONS IN THE CONTEXT OF THE FOOD SYSTEMS SUMMIT

The livestock sector will change, voluntarily, or as a result of forces external to the sector. Our paper provided a synthesis of the demand and supply dynamics of ASF, their nutritional, health, and environmental impacts, and the environmental trade-offs arising from the uses of land and natural resources. We also showed some alternative pathways of how the sector could develop depending on the goals and aspirations of different countries. In this sense, context is very important, as what may work in one place may not be suitable for another. This initial targeting will be fundamental to design actions and policies that profoundly improve and substantially change, in many cases, the way we think about the roles of livestock.

Our study has demonstrated that the dynamism of the livestock sector provides a range of avenues for change, some more relevant to smallholders than others, and some more amenable to public funding than others, and some more likely to alleviate negative environmental impacts than others. Picking the most effective and desirable solutions will be essential for stakeholders associated with the livestock sector to achieve the desired impacts on sustainable food systems. The balance between social and environmental goals will need to be carefully evaluated. The avenues for growth, the trade-offs and the potential actions can be summarised below.

Smallholder dairy: The evidence suggests that demand is growing fast for milk, and that at least in highland or high potential areas, productivity per animal is increasing due to the adoption of better practices like feeds, animal health management and genetics. These systems can be competitive, but issues surrounding land fragmentation and feed availability need closer attention. Testing and implementing transformational feed technologies or engaging in developing systems that could increase in circularity, through increased biomass recycling sound like important next steps to ensure high-quality feed at low environmental costs in these systems. This needs to go beyond previous work on crop residues (e.g. Blummel and colleagues) and may need transdisciplinary partnerships with other sectors to develop these new biomass streams and to adjust breeding and feeding strategies. This in turn would also lead to reduced pressures on land and to the exploration of other greenhouse gas mitigation avenues, beyond those explored to date (improved feeds, manure management). Eventually this could contribute to national mitigation action plans of specific countries.

The future of the smallholder pork and poultry sector: our synthesis has shown that while there are countries were smallholder pork and poultry make an important contribution to the supply of these products, in the coming decades, much of the growth in production is likely to come from industrial production, as integrated supply chains emerge and the private sector engagement increases. This suggests that investing in these smallholder systems is at best a medium-term strategy that could provide livelihood benefits as these producers diversify or identify new exit strategies. Identifying transition options for these producers in the future seems necessary.

From an international public good perspective, the future of feed for fuelling the large demand for pork and poultry is a critical researchable issue, if the feed is to be sourced sustainably. Biomass value chains, old and new, need to be evaluated, developed and promoted to ensure that competition for food with humans is minimised. Here, again the development of circular feed sources, the development of regulations for including a minimum amount of recycled feed, and the development of new feed sources (superfeeds from industrial production or others) need to be developed and business cases for local industries to take on these enterprises in a well-planned manner.

For monogastrics, there are a lot of researchable issues, including on antimicrobial resistance, with priority areas being:

1. Monitoring inputs: what inputs are used in the system in terms of feed, antimicrobials and other aspects that affect the health of the animals and have implications on the health of producers, consumers and those working in the food chain.
2. Surveillance: establishing systems that generate information on current and emerging diseases, antimicrobial use and antimicrobial resistance.
3. Assessment of the economic burden of livestock health and wealth (see https://animalhealthmetrics.org) as a basis to identify interventions that impact positively on the economic outcomes of livestock production as well as minimising impacts on the environment and public health.

A central element of a livestock agenda in relation to environmental trade-offs is related to the identification of entry points for engaging in the beef sector. On one hand, the existing data shows that most of the growth in red meat production has been obtained through increases in animal numbers, while intensification has been influential in only a few countries. Consumption per capita is stagnant, or decreasing in most countries, and most of the demand is driven by population growth. At the same time, reducing red meat consumption could lead to substantial greenhouse gas mitigation, reductions in pressure on land and biodiversity. Producing red meat only from lands of low opportunity costs, or as a by-product from the dairy industry would have the lowest environmental impacts.

Identifying the best levels of consumption in relation to other dietary elements for different population groups should be a high priority for the Food Systems Summit, as well as identifying ways to decouple red meat production from land, or create niche products for very specific sets of consumers through labelling systems and certification.

The livestock sector will change, voluntarily, or as a result of forces external to the sector. If sustainability concerns are of paramount importance, a critical research area is to develop economic incentive systems (price premiums) and regulations to pay for reduced emissions, watershed protection, biodiversity protection and others; and to internalise these in true cost or true-pricing schemes, supported by adequate regulatory and fiscal measures.

REFERENCES

1. Afshin, A. et al. (2019) 'Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017', The Lancet, 393(10184), pp. 1958–1972. doi: 10.1016/S0140-6736(19)30041-8.
2. Agarwal, B. (2018) 'Gender equality, food security and the sustainable development goals', Current Opinion in Environmental Sustainability, 34, pp. 26–32. doi: 10.1016/j.cosust.2018.07.002.
3. Aleksandrowicz, L. et al. (2016) 'The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review', PLoS ONE, 11(11), p. e0165797. doi: 10.1371/journal.pone.0165797.
4. Alexander, P. et al. (2017) 'Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?', Global Food Security. Elsevier B.V., pp. 22–32. doi: 10.1016/j.gfs.2017.04.001.
5. Alexandratos, N. and Bruinsma, J. (2012) World Agriculture towards 2030/2050: the 2012 revision, ESA Working Paper No. 12-03. Available at: www.fao.org/economic/esa (Accessed: 22 December 2018).
6. Annan, R. A. et al. (2018) 'Public awareness and perception of Ghana's restrictive policy on fatty meat, as well as preference and consumption of meat products among Ghanaian adults living in the Kumasi Metropolis', BMC Nutrition, 4(1), pp. 1–8. doi: 10.1186/s40795-018-0209-z.
7. Baker, L. et al. (2020) 'Prospects for the true cost accounting of food systems', Nature Food, 1(12), pp. 765–767. doi: 10.1038/s43016-020-00193-6.
8. Baltussen, W. et al. (2016) Valuation of livestock eco-agri-food systems: poultry, beef and dairy. Wageningen. doi: 10.18174/389545.
9. Baltussen, W. et al. (2019) Traditional livestock systems in Tanzania; An application of the TEEBAgriFood Evaluation Framework. Available at: https://flic.kr/p/3qRfW2 (Accessed: 21 June 2021).
10. Barange, B. et al. (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Rome.
11. Beal, T. et al. (2017) 'Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes', PLoS ONE, 12(4), p. e0175554. doi: 10.1371/journal.pone.0175554.
12. Van Boeckel, T. P. et al. (2015) 'Global trends in antimicrobial use in food animals', Proceedings of the National Academy of Sciences of the United States of America, 112(18), pp. 5649–5654. doi: 10.1073/pnas.1503141112.
13. Bridges, M. (2018) 'Moo-ove Over, Cow's Milk: The Rise of Plant-Based Dairy Alternatives', Practical Gastroenterology, 21.
14. Brunton, L. A. et al. (2019) 'Identifying hotspots for antibiotic resistance emergence and selection, and elucidating pathways to human exposure: Application of a systems-thinking approach to aquaculture systems', Science of the Total Environment, 687, pp. 1344–1356. doi: 10.1016/j.scitotenv.2019.06.134.
15. Burkholder, J. A. et al. (2007) 'Impacts of waste from concentrated animal feeding operations on water quality', Environmental Health Perspectives, 115(2), pp. 308–312. doi: 10.1289/ehp.8839.
16. Burton, R. J. F. (2019) 'The potential impact of synthetic animal protein on livestock production: The new "war against agriculture"?', Journal of Rural Studies, 68, pp. 33–45. doi: 10.1016/j.jrurstud.2019.03.002.
17. Campbell, D. L. M. et al. (2018) 'Virtual fencing of cattle using an automated collar in a feed attractant trial', Applied Animal Behaviour Science, 200(May 2017), pp. 71–77. doi: 10.1016/j.applanim.2017.12.002.
18. Capper, J. L., Cady, R. A. and Bauman, D. E. (2009) 'The environmental impact of dairy production: 1944 compared with 2007', Journal of animal science, 87(6), pp. 2160–2167. doi: 10.2527/jas.2009-1781.
19. Clark, M. A. et al. (2020) 'Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets', Science, 370(6517), pp. 705–708. doi: 10.1126/science.aba7357.
20. CSIRO (2021) FutureFeed. Available at: https://www.future-feed.com/ (Accessed: 18 June 2021).
21. Davis, K. F. et al. (2015) 'Historical trade-offs of livestock's environmental impacts', Environmental Research Letters, 10(12), p. 125013. doi: 10.1088/1748-9326/10/12/125013.
22. Delgado, C. L. et al. (1999) The Coming Livestock Revolution, Commission on Sustainable Development. New York. doi: 10.1007/s10680-008-9165-7.
23. Delgado, C. L. (2003) 'Rising Consumption of Meat and Milk in Developing Countries Has Created a New Food Revolution', The Journal of Nutrition, 133, pp. 3965–3971. doi: 0022-3166/03.
24. Dinerstein, E. et al. (2017) 'An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm', BioScience, 67(6), pp. 534–545. doi: 10.1093/biosci/bix014.
25. Du, Z. et al. (2021) 'Exploring microbial community structure and metabolic gene clusters during silage fermentation of paper mulberry, a high-protein woody plant', Animal Feed Science and Technology, 275, p. 114766. doi: 10.1016/j.anifeedsci.2020.114766.

26. Eaton, J. C. et al. (2019) 'Effectiveness of provision of animal-source foods for supporting optimal growth and development in children 6 to 59 months of age', Cochrane Database of Systematic Reviews, 2019(5). doi: 10.1002/14651858.CD012818.pub2.
27. FAO (2006) Livestock Report 2006. Rome. Available at: http://www.fao.org/3/a0255e/a0255e.pdf (Accessed: 5 April 2019).
28. FAO (2009) The state of food and agriculture: Livestock in balance, Food and Agriculture Organisation of the United Nations, Rome 2009. doi: 10.1016/S0140-6736(75)92740-3.
29. FAO (2013) Food wastage footprint: Impacts on natural resources. Rome. Available at: www.fao.org/publications (Accessed: 18 June 2021).
30. FAO (2016) The State of World Fisheries and Aquaculture 2016 - Contributing to food security and nutrition for all. Rome. Available at: www.fao.org/publications (Accessed: 18 June 2021).
31. FAO (2018) The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Rome. Available at: www.fao.org/publications (Accessed: 10 June 2021).
32. FAO (2019a) FAO's work on climate change - Fisheries & aquaculture. Rome.
33. FAO (2019b) FAOSTAT. Available at: http://www.fao.org/faostat/en/#data/TM (Accessed: 2 July 2021).
34. FAO, OIE and WHO (2010) The FAO-OIE-WHO Collaboration Sharing responsibilities and coordinating global activities to address health risks at the animal-human-ecosystems interfaces.
35. FAO and UNEP (2020) The State of the World's Forests 2020: Forests, biodiversity and people. Rome. Available at: http://www.fao.org/3/ca8642en/ca8642en.pdf (Accessed: 18 June 2021).
36. FAOSTAT (2018) FAOSTAT Food Balance Sheets. Available at: http://www.fao.org/faostat/en/#data/FBS (Accessed: 16 June 2021).
37. Fiorella, K. J. et al. (2019) 'A review of transactional sex for natural resources: Under-researched, overstated, or unique to fishing economies?', Global Public Health, 14(12), pp. 1803–1814. doi: 10.1080/17441692.2019.1625941.
38. Frehner, A. et al. (2021) 'How food choices link sociodemographic and lifestyle factors with sustainability impacts', Journal of Cleaner Production, 300, p. 126896. doi: 10.1016/j.jclepro.2021.126896.
39. Galloway, J. N. et al. (2007) 'International Pork Chop Trade in Meat: The Tip of the', Ambio, 36(8), pp. 622–629. doi: 10.1579/0044-7447(2007)36[622:ITIMTT]2.0.CO;2.
40. Garnett, T. et al. (2013) 'Sustainable Intensification in Agriculture: Premises and Policies', Science Magazine, 341(July), pp. 33–34. doi: 10.1126/science.1234485.
41. Garnett, T. et al. (2015) 'Policies and actions to shift eating patterns: What works?', FCRN/Chatham House, p. 85. Available at: http://www.fcrn.org.uk/sites/default/files/fcrn_chatham_house_0.pdf.
42. GBD 2017 Mortality Collaborators, D. et al. (2018) 'Global, regional, and national age-sex-specific mortality and life expectancy, 1950-2017: a systematic analysis for the Global Burden of Disease Study 2017.', Lancet (London, England), 392(10159), pp. 1684–1735. doi: 10.1016/S0140-6736(18)31891-9.
43. Gemeda, B. A. et al. (2020) 'Antimicrobial Use in Extensive Smallholder Livestock Farming Systems in Ethiopia: Knowledge, Attitudes, and Practices of Livestock Keepers', Frontiers in Veterinary Science, 7, p. 55. doi: 10.3389/fvets.2020.00055.
44. Gemmill-Herren, B., Baker, L. E. and Daniels, P. A. (2021) True Cost Accounting for Food: Balancing the Scale. Available at: https://www.routledge.com/True-Cost-Accounting-for-Food-Balancing-the-Scale/Gemmill-Herren-Baker-Daniels/p/book/9780367506858 (Accessed: 21 June 2021).
45. Gerhardt, C. et al. (2020) 'How will cultured meat and meat alternatives disrupt the agricultural and food industry?', Industrial Biotechnology, 16(5), pp. 262–270. doi: 10.1089/ind.2020.29227.cge.
46. Gilbert, M. et al. (2015) 'Income disparities and the global distribution of intensively farmed chicken and pigs', PLoS ONE, 10(7), pp. 1–14. doi: 10.1371/journal.pone.0133381.
47. Godde, C. M. et al. (2018) 'Grazing systems expansion and intensification: Drivers, dynamics, and trade-offs', Global Food Security, 16(November), pp. 93–105. doi: 10.1016/j.gfs.2017.11.003.
48. Godfray, H. C. J. et al. (2018) 'Meat consumption, health, and the environment', Science, 361(6399). doi: 10.1126/science.aam5324.
49. Griscom, B. W. et al. (2017) 'Natural climate solutions', Proceedings of the National Academy of Sciences, Early edit, pp. 1–6. doi: 10.1073/pnas.1710465114.
50. Hallström, E., Carlsson-Kanyama, A. and Börjesson, P. (2015) 'Environmental impact of dietary change: A systematic review', Journal of Cleaner Production, 91, pp. 1–11. doi: 10.1016/j.jclepro.2014.12.008.
51. Havlík, P. et al. (2014) 'Climate change mitigation through livestock system transitions', Proceedings of the National Academy of Sciences of the Unit-

ed States of America, 111(10), pp. 3709–14. doi: 10.1073/pnas.1308044111.

52. Headey, D. D. and Alderman, H. H. (2019) 'The Relative Caloric Prices of Healthy and Unhealthy Foods Differ Systematically across Income Levels and Continents', Journal of Nutrition, 149(11), pp. 2020–2033. doi: 10.1093/jn/nxz158.
53. Headey, D., Hirvonen, K. and Hoddinott, J. (2018) 'Animal Sourced Foods and Child Stunting', American Journal of Agricultural Economics, 100(5), pp. 1302–1319. doi: 10.1093/ajae/aay053.
54. Henchion, M. et al. (2017) 'Future protein supply and demand: Strategies and factors influencing a sustainable equilibrium', Foods, 6(7), pp. 1–21. doi: 10.3390/foods6070053.
55. Herrero, M. et al. (2009) 'Livestock, livelihoods and the environment: understanding the trade-offs', Current Opinion in Environmental Sustainability, 1(2), pp. 111–120. doi: 10.1016/j.cosust.2009.10.003.
56. Herrero, M. et al. (2010) 'Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems', Science, 327(5967), pp. 822–825. doi: 10.1126/science.1183725.
57. Herrero, M., Havlík, P., et al. (2013) 'Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems.', Proceedings of the National Academy of Sciences of the United States of America, 110(52), pp. 20888–93. doi: 10.1073/pnas.1308149110.
58. Herrero, M., Grace, D., et al. (2013) 'The roles of livestock in developing countries', in Animal. Elsevier, pp. 3–18. doi: 10.1017/S1751731112001954.
59. Herrero, M. et al. (2014) 'Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models', Global Environmental Change, 24(1), pp. 165–182. doi: 10.1016/j.gloenvcha.2013.12.008.
60. Herrero, M. et al. (2016) 'Greenhouse gas mitigation potentials in the livestock sector', Nature Climate Change, 6(5), pp. 452–461. doi: 10.1038/nclimate2925.
61. Herrero, M., Thornton, Philip K, et al. (2017) 'Farming and the geography of nutrient production for human use: a transdisciplinary analysis', Lancet Planet Health, 1(1), pp. e33–e42. doi: 10.1016/S2542-5196(17)30007-4.
62. Herrero, M., Thornton, Philip K., et al. (2017) 'Farming and the geography of nutrient production for human use: a transdisciplinary analysis', The Lancet Planetary Health, 1(1), pp. e33–e42. doi: 10.1016/S2542-5196(17)30007-4.
63. Herrero, M. et al. (2020) 'Innovation can accelerate the transition towards a sustainable food system', Nature Food, 1(5), pp. 266–272. doi: 10.1038/s43016-020-0074-1.
64. Herrero, M. et al. (2021) 'Articulating the effect of food systems innovation on the Sustainable Development Goals', The Lancet Planetary Health, 5(1), pp. e50–e62. doi: 10.1016/S2542-5196(20)30277-1.
65. Hristov, A. N. et al. (2013) Mitigation of greenhouse gas emissions in livestock production. A review of technical options for non-CO2 emissions, FAO Animal Production and Health Paper. Edited by P. J. Gerber, B. Henderson, and H. P. S. Makkar. Rome. doi: 10.1016/j.agee.2005.08.009.
66. Hu, F. B. (2013) 'Resolved: There is sufficient scientific evidence that decreasing sugar-sweetened beverage consumption will reduce the prevalence of obesity and obesity-related diseases', Obesity Reviews, 14(8), pp. 606–619. doi: 10.1111/obr.12040.
67. IARC (2015) IARC Monographs evaluate consumption of red meat and processed meat. Available at: http://www.iarc.fr/en/media-centre/iarcnews/pdf/Monographs-Q&A_Vol114.pdf (Accessed: 18 June 2021).
68. IFCN (no date) IFCN - Dairy Data · Knowledge · Inspiration - IFCN Dairy Research Network. Available at: https://ifcndairy.org/ (Accessed: 18 June 2021).
69. IMF (2017) IMF Primary Commodity Prices. Available at: https://www.imf.org/en/Research/commodity-prices (Accessed: 18 June 2021).
70. Jackson, J. B. C. et al. (2001) 'Historical overfishing and the recent collapse of coastal ecosystems', Science, 293(5530), pp. 629–637. doi: 10.1126/science.1059199.
71. Johnston, B. C. et al. (2019) 'Unprocessed red meat and processed meat consumption: Dietary guideline recommendations from the nutritional recommendations (NUTRIRECS) consortium', Annals of Internal Medicine, 171(10), pp. 756–764. doi: 10.7326/M19-1621.
72. Keerie, M. (2021) Record $3.1 billion invested in alt proteins in 2020 signals growing market momentum, The Good Food Institute. Available at: https://gfi.org/blog/2020-state-of-the-industry-highlights/ (Accessed: 21 June 2021).
73. Kemper, B. (2018) 'Nut Milks Are Milk, Says Almost Every Culture Across the Globe', Smithsonian Magazine. Available at: https://www.smithsonianmag.com/history/nut-milks-are-milk-says-almost-every-culture-across-globe-180970008/ (Accessed: 21 June 2021).
74. Leclère, D. et al. (2018) 'Towards pathways bending the curve of terrestrial biodiversity trends within the 21 st century', Preprint. doi: 10.22022/ESM/04-2018.15241.

75. Lennox, G. D. et al. (2018) 'Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests', Global Change Biology, 24(12), pp. 5680–5694. doi: 10.1111/gcb.14443.
76. Leroy, A. et al. (2020) Seafood Sustainability Stability and Security: How the sustainability of fisheries management impacts the stability and security of countries, and what we must do about it. Brussels. doi: 10.1371/journal.pone.0004570.
77. Marlatt, K. L. et al. (2016) 'Breakfast and fast food consumption are associated with selected biomarkers in adolescents', Preventive Medicine Reports, 3, pp. 49–52. doi: 10.1016/j.pmedr.2015.11.014.
78. Mason-D'Croz, D. et al. (2020) 'Modelling the global economic consequences of a major African swine fever outbreak in China', Nature Food, 1(4), pp. 221–228. doi: 10.1038/s43016-020-0057-2.
79. Mattick, C. S. et al. (2015) 'Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States', Environmental Science and Technology, 49(19), pp. 11941–11949. doi: 10.1021/acs.est.5b01614.
80. Mbow, C. et al. (2019) 'Food Security', in IPCC Special Report on Climate Change and Land. IPCC, pp. 1–200.
81. McDermott, J. J. et al. (2010) 'Sustaining intensification of smallholder livestock systems in the tropics', Livestock Science, 130(1–3), pp. 95–109. doi: 10.1016/j.livsci.2010.02.014.
82. Mills, D. J. et al. (2011) 'Under-reported and undervalued: Small-scale fisheries in the developing world', in Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World. CABI Publishing, pp. 1–15. doi: 10.1079/9781845936075.0001.
83. Mozaffarian, D. (2016) 'Dietary and Policy Priorities for Cardiovascular Disease, Diabetes, and Obesity', Circulation, 133(2), pp. 187–225. doi: 10.1161/CIRCULATIONAHA.115.018585.
84. Murphy, S. P. and Allen, L. H. (2003) 'Nutritional Importance of Animal Source Foods', in Journal of Nutrition. American Institute of Nutrition, pp. 3932–3935. doi: 10.1093/jn/133.11.3932s.
85. Neufeld, L. M., Hendriks, S. and Hugas, M. (2021) The Scientific Group for the UN Food Systems Summit Healthy diet: A definition for the United Nations Food Systems Summit 2021. Available at: https://sc-fss2021.org/ (Accessed: 18 June 2021).
86. Neumann, C., Harris, D. M. and Rogers, L. M. (2002) 'Contribution of animal source foods in improving diet quality and function in children in the developing world', Nutrition Research, 22(1–2), pp. 193–220. doi: 10.1016/S0271-5317(01)00374-8.
87. Newbold, T. et al. (2016) 'Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment', Science, 353(6296), pp. 291–288. doi: 10.1126/science.aaf2201.
88. Olff, H. and Ritchie, M. E. (1998) 'Effects of herbivores on grassland plant diversity', Trends in Ecology and Evolution, 13(7), pp. 261–265. doi: 10.1016/S0169-5347(98)01364-0.
89. Pan, A. et al. (2011) 'Red meat consumption and risk of type 2 diabetes: 3 Cohorts of US adults and an updated meta-analysis', American Journal of Clinical Nutrition, 94(4), pp. 1088–1096. doi: 10.3945/ajcn.111.018978.
90. Parodi, A. et al. (2018) 'The potential of future foods for sustainable and healthy diets', Nature Sustainability, 1(12), pp. 782–789. doi: 10.1038/s41893-018-0189-7.
91. Phu, D. H. et al. (2021) 'Reducing Antimicrobial Usage in Small-Scale Chicken Farms in Vietnam: A 3-Year Intervention Study', Frontiers in Veterinary Science, 7, p. 1244. doi: 10.3389/fvets.2020.612993.
92. Pikaar, I. et al. (2018) 'Decoupling Livestock from Land Use through Industrial Feed Production Pathways', Environmental Science and Technology, 52(13), pp. 7351–7359. doi: 10.1021/acs.est.8b00216.
93. Poore, J. and Nemecek, T. (2018) 'Reducing food's environmental impacts through producers and consumers', Science, 360(6392), pp. 987–992. doi: 10.1126/science.aaq0216.
94. Poux, X. and Aubert, P. (2018) An agroecological Europe in 2050: multifunctional agriculture for healthy eating Findings from the Ten Years For Agroecology (TYFA) modelling exercise. Paris. Available at: www.iddri.org (Accessed: 18 June 2021).
95. Qian, F. et al. (2020) 'Red and processed meats and health risks: How strong is the evidence?', Diabetes Care, 43(2), pp. 265–271. doi: 10.2337/dci19-0063.
96. Raasch, S. et al. (2020) 'Effectiveness of alternative measures to reduce antimicrobial usage in pig production in four European countries', Porcine Health Management, 6(1), pp. 1–12. doi: 10.1186/s40813-020-0145-6.
97. Ramankutty, N. et al. (2018) 'Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security', Annual Review of Plant Biology, 69(1), pp. 789–815. doi: 10.1146/annurev-arplant-042817-040256.
98. Ravuvu, A. et al. (2018) 'Protocol to monitor trade agreement food-related aspects: The Fiji case study', Health Promotion International, 33(5), pp. 887–900. doi: 10.1093/heapro/dax020.

99. Robinson, T. P. et al. (2011) Global livestock production systems, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI),.
100. Roe, S. et al. (2019) 'Contribution of the land sector to a 1.5 °C world', Nature Climate Change, 9(11), pp. 817–828. doi: 10.1038/s41558-019-0591-9.
101. Rubio, N. R., Xiang, N. and Kaplan, D. L. (2020) 'Plant-based and cell-based approaches to meat production', Nature Communications, 11(1), pp. 1–11. doi: 10.1038/s41467-020-20061-y.
102. Saget, C., Vogt-Schilb, A. and Luu, T. (2020) Jobs in a Net-Zero Emissions Future in Latin America and the Caribbean. Washington D.C. and Geneva. Available at: https://www.ilo.org/wcmsp5/groups/public/---americas/---ro-lima/documents/publication/wcms_752069.pdf (Accessed: 18 June 2021).
103. Santo, R. E. et al. (2020) 'Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective', Frontiers in Sustainable Food Systems, 4, p. 134. doi: 10.3389/fsufs.2020.00134.
104. Searchinger, T. D. et al. (2015) 'High carbon and biodiversity costd from converting Africa's wet savannahs to cropland', Nature Climate Change, 5, pp. 481–486. doi: 10.1038/NCLIMATE2584.
105. Semba, R. D. et al. (2016) 'Child Stunting is Associated with Low Circulating Essential Amino Acids', EBioMedicine, 6, pp. 246–252. doi: 10.1016/j.ebiom.2016.02.030.
106. Shapiro, M. J. et al. (2019) 'A Systematic Review Investigating the Relation between Animal-Source Food Consumption and Stunting in Children Aged 6-60 Months in Low and Middle-Income Countries', Advances in Nutrition, 10(5), pp. 827–847. doi: 10.1093/advances/nmz018.
107. Sheikh (2019) 'Got Impossible Milk? The Quest for Lab-Made Dairy', The New York Times, 2 August. Available at: https://www.nytimes.com/2019/08/02/science/lab-grown-milk.html (Accessed: 21 June 2021).
108. Shurtleff, W. and Aoyagi, A. (2014) History of Meat Alternatives (965 CE to 2014): Extensively Annotated Bibliography and Sourcebook. Soyinfo Center. Available at: https://www.soyinfocenter.com/pdf/179/MAL.pdf (Accessed: 21 June 2021).
109. Smith, A. (2014) 'The History of the Veggie Burger', Smithsonian Magazine. Available at: https://www.smithsonianmag.com/arts-culture/history-veggie-burger-180950163/ (Accessed: 21 June 2021).
110. Smith, P. et al. (2007) 'Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture', Agriculture, Ecosystems and Environment, 118(1–4), pp. 6–28. doi: 10.1016/j.agee.2006.06.006.
111. Smith, P. et al. (2014) 'Agriculture, Forestry and Other Land Use', in Intergovernmental Panel on Climate Change Working Group (ed.) Change 2014: Mitigation of Climate Change, p. 94. doi: 10.1016/j.phrs.2011.03.002.
112. Springmann, M. et al. (2016) 'Analysis and valuation of the health and climate change cobenefits of dietary change', Proceedings of the National Academy of Sciences of the United States of America, 113(15), pp. 4146–4151. doi: 10.1073/pnas.1523119113.
113. Springmann, M. et al. (2018) 'Options for keeping the food system within environmental limits', Nature, 562(7728), pp. 519–525. doi: 10.1038/s41586-018-0594-0.
114. Stehfest, E. et al. (2009) 'Climate benefits of changing diet', Climatic Change, 95(1–2), pp. 83–102. doi: 10.1007/s10584-008-9534-6.
115. De Sy, V. et al. (2015) 'Land use patterns and related carbon losses following deforestation in South America', Environmental Research Letters, 10(12), p. 124004. doi: 10.1088/1748-9326/10/12/124004.
116. Thornton, P. and Herrero, M. (2010) Development and Climate Change: The inter-linkages between rapid growth in livestock production, climate change, and the impacts on water resources, land use, and deforestation. Nairobi.
117. Thornton, P. K. (2010) 'Livestock production: Recent trends, future prospects', Philosophical Transactions of the Royal Society B: Biological Sciences. Royal Society, pp. 2853–2867. doi: 10.1098/rstb.2010.0134.
118. Thow, A. M. et al. (2017) 'Food supply, nutrition and trade policy: Reversal of an import ban on Turkey tails', Bulletin of the World Health Organization, 95(10), pp. 723–725. doi: 10.2471/BLT.17.192468.
119. Tilman, D. and Clark, M. (2014) 'Global diets link environmental sustainability and human health', Nature, 515(7528), pp. 518–522. doi: 10.1038/nature13959.
120. Troell, M., Jonell, M. and Crona, B. (2019) The role of seafood in sustainable and healthy diets The EAT-Lancet Commission report through a blue lens. Stockholm.
121. Tubiello, F. N. et al. (2021) 'Carbon emissions and removals from forests: New estimates, 1990-2020', Earth System Science Data, 13(4), pp. 1681–1691. doi: 10.5194/essd-13-1681-2021.
122. Vanhercke, T. et al. (2017) 'Step changes in leaf oil accumulation via iterative metabolic engi-

neering', Metabolic Engineering, 39, pp. 237–246. doi: 10.1016/j.ymben.2016.12.007.

123. de Vries, M. and de Boer, I. J. M. (2010) 'Comparing environmental impacts for livestock products: A review of life cycle assessments', Livestock Science, 128(1–3), pp. 1–11. doi: 10.1016/J.LIVSCI.2009.11.007.
124. Waithaka, M. M. et al. (2006) 'Bio-economic evaluation of farmers' perceptions of viable farms in western Kenya', Agricultural Systems, 90(1–3), pp. 243–271. doi: 10.1016/j.agsy.2005.12.007.
125. Walker, P. et al. (2005) 'Public health implications of meat production and consumption', Public Health Nutrition, 8(4), pp. 348–356. doi: 10.1079/phn2005727.
126. Walsh, B. J. et al. (2015) 'New feed sources key to ambitious climate targets', Carbon Balance and Management, 10, pp. 1–8. doi: 10.1186/s13021-015-0040-7.
127. WHO (2015) Cancer: Carcinogenicity of the consumption of red meat and processed meat. Available at: https://www.who.int/news-room/q-a-detail/cancer-carcinogenicity-of-the-consumption-of-red-meat-and-processed-meat (Accessed: 1 July 2021).
128. Wieland, B. et al. (2019) AMUSE Livestock, version 2-Antimicrobial use in livestock production A tool to harmonise data collection on knowledge, attitude and practices. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/107443/AMUSE_livestock_v2.pdf?sequence=2&isAllowed=y (Accessed: 21 June 2021).
129. Willett, W. et al. (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', The Lancet, 393, pp. 447–429. doi: 10.1016/S0140-6736(18)31788-4.
130. Wing, S. and Wolf, S. (2000) 'Intensive livestock operations, health, and quality of life among eastern North Carolina residents', Environmental Health Perspectives, 108(3), pp. 233–238. doi: 10.1289/ehp.00108233.
131. World Bank (2016) 'List of economies'. Available at: http://databank.worldbank.org/data/download/site-content/CLASS.xls.
132. Young, V. and Pellett, P. (1994) 'Plant protein in relation to human protein and amino acid nutrition', American Journal of Clinical Nutrition, 59, pp. 1203S-1212S. Available at: http://pilarmartinescudero.es/Ene2018/Plan protein in relation to human protein .pdf (Accessed: 21 June 2021).
133. Zaharia, S. et al. (2021) 'Sustained intake of animal-sourced foods is associated with less stunting in young children', Nature Food, 2(4), pp. 246–254. doi: 10.1038/s43016-021-00259-z.
134. Van Zanten, H. H. E. et al. (2018) 'Defining a land boundary for sustainable livestock consumption', Global Change Biology, 24(9), pp. 4185–4194. doi: 10.1111/gcb.14321.

SUPPLEMENTARY INFORMATION

Figure S 1 Percent change in per capita animal source-food demand 1990-2015. Source: Based on authors' calculations from FAOSTAT (2018).

	Fish, Seafood	Milk - Excluding Butter	Eggs	Meat	Bovine Meat	Mutton & Goat Meat	Pigmeat	Poultry Meat
Europe	25.1%	12.8%	5.2%	2.5%	-40.1%	-47.5%	2.5%	81.2%
Northern Africa	171.5%	75.1%	44.6%	74.3%	51.7%	48.6%	-64.4%	143.8%
Western Africa	73.8%	50.1%	15.7%	27.7%	4.9%	57.9%	38.1%	113.6%
Eastern Africa	-18.1%	68.2%	-10.0%	5.2%	-2.8%	-4.2%	32.6%	27.3%
Middle Africa	32.2%	-27.5%	70.1%	67.0%	-13.8%	34.3%	160.7%	998.8%
Southern Africa	-22.6%	15.9%	89.2%	72.1%	-8.0%	-25.3%	98.8%	220.4%
Eastern Asia	97.2%	344.8%	127.3%	128.6%	150.3%	241.0%	95.8%	213.8%
China	180.8%	6670.3%	149.5%	145.3%	312.3%	292.3%	98.5%	200.7%
Central Asia	59.7%	32.8%	68.8%	30.3%	9.4%	-6.6%	62.1%	653.4%
Southern Asia	75.0%	66.1%	113.5%	24.6%	-17.0%	-35.0%	-46.7%	341.0%
India	51.5%	71.7%	158.8%	3.9%	-49.6%	-11.7%	-47.2%	501.1%
South-Eastern Asia	94.2%	72.3%	77.5%	124.7%	53.0%	57.0%	128.9%	167.8%
Western Asia	30.8%	7.5%	15.6%	72.7%	40.5%	-26.2%	0.0%	154.8%
Americas	6.5%	7.8%	31.3%	26.8%	-2.5%	-21.4%	9.5%	80.4%
United States of America	2.5%	-1.4%	8.3%	4.9%	-13.1%	-42.4%	-5.4%	32.2%
South America	25.3%	32.7%	45.3%	62.1%	13.7%	-32.1%	50.8%	180.2%
Brazil	100.7%	62.1%	15.6%	80.2%	40.8%	-31.0%	44.4%	181.5%
Oceania	38.5%	-14.6%	-27.5%	7.4%	-16.8%	-60.4%	40.2%	105.6%
Australia	40.2%	-7.4%	-21.6%	6.3%	-14.0%	-64.4%	35.4%	100.8%
World	53.1%	26.1%	47.5%	34.5%	-6.2%	14.0%	25.8%	106.3%

Percent change in per capita food demand: -60.0% to 300.0%

Figure S 2 Evolution of livestock numbers by region during the period of 1961-2013. Data from FAOSTAT(2018), as presented in Ramankutty et al. (2018).

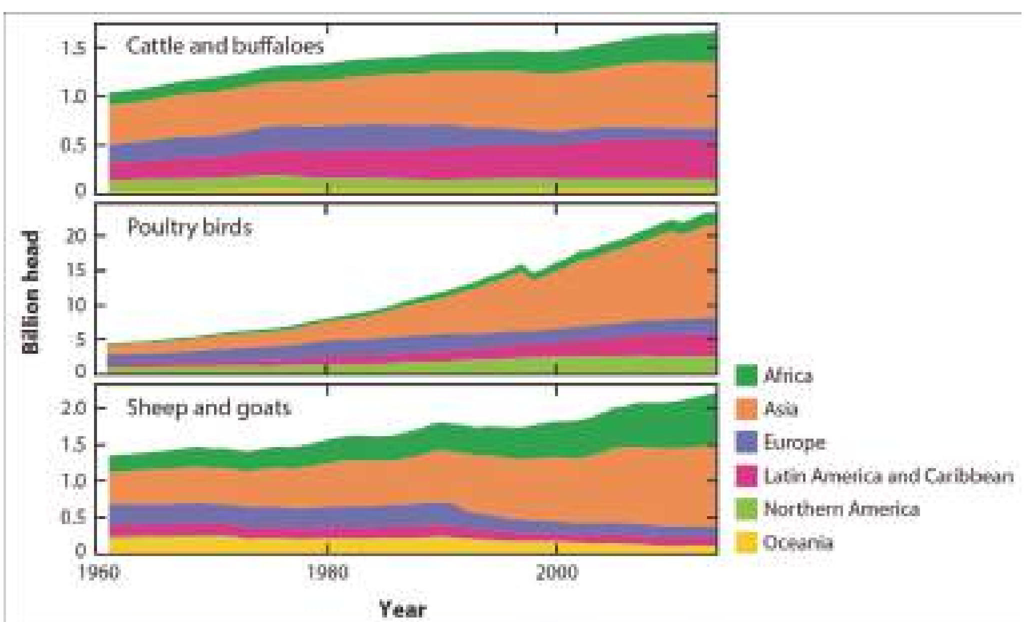


Figure S 3 Modelled proportions of extensive, semi-intensive and intensive pig production in different parts of the world in relation to the gross domestic product (GDP, in Purchasing Power Parity (PPP)) (Gilbert et al., 2015).

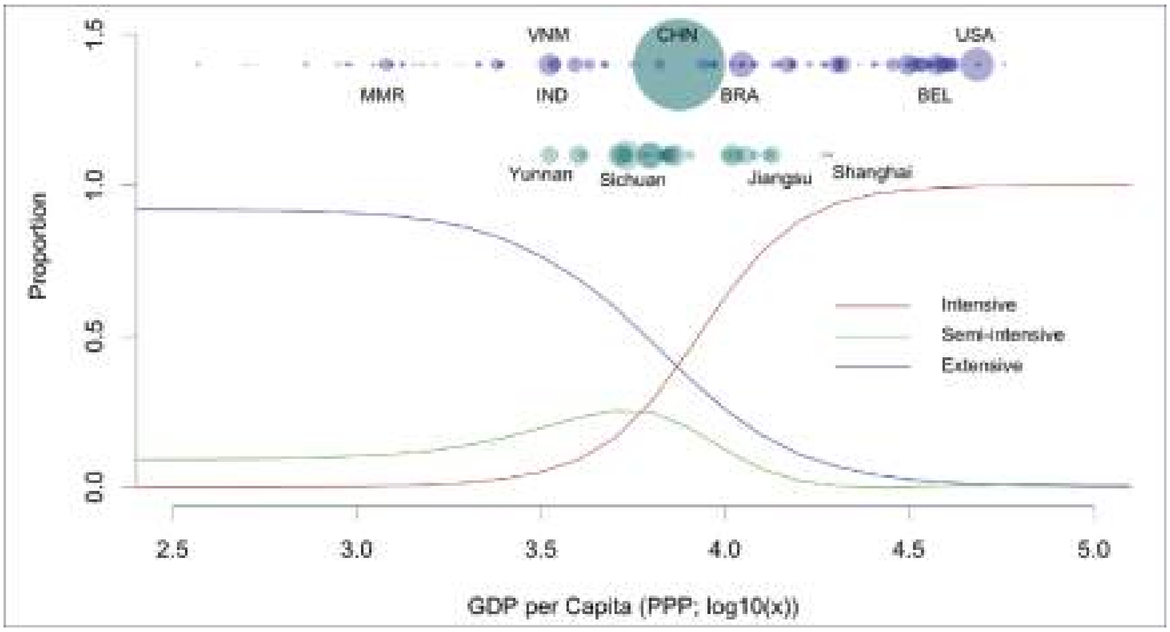


Figure S 4 Trends in land use for cropland and permanent pastures 1700-2013 (Ramankutty et al., 2018).

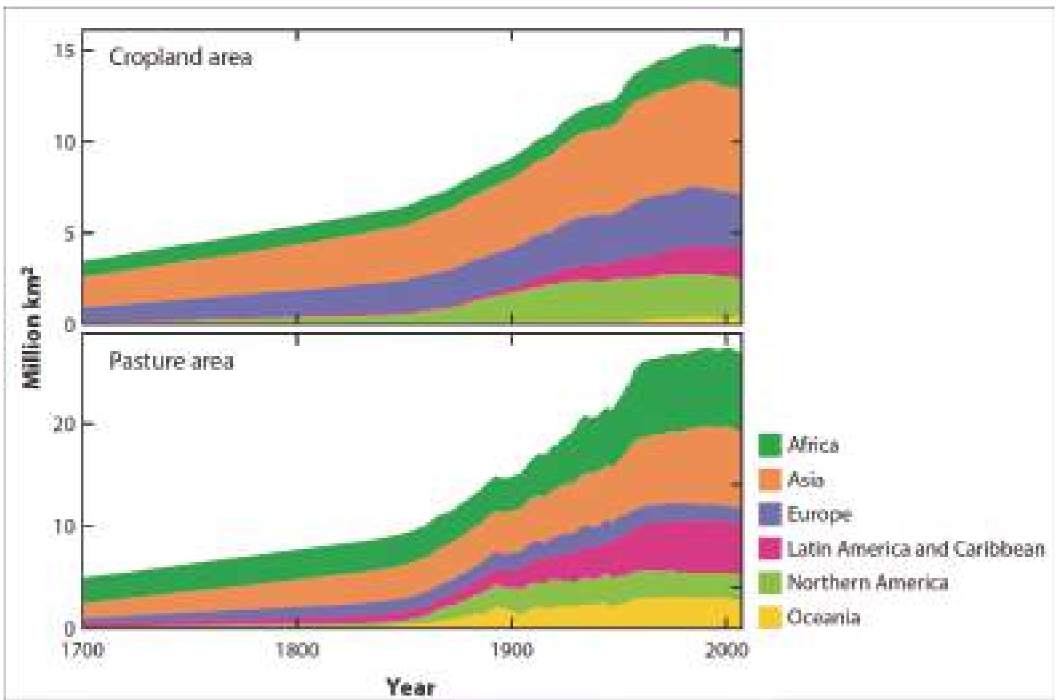
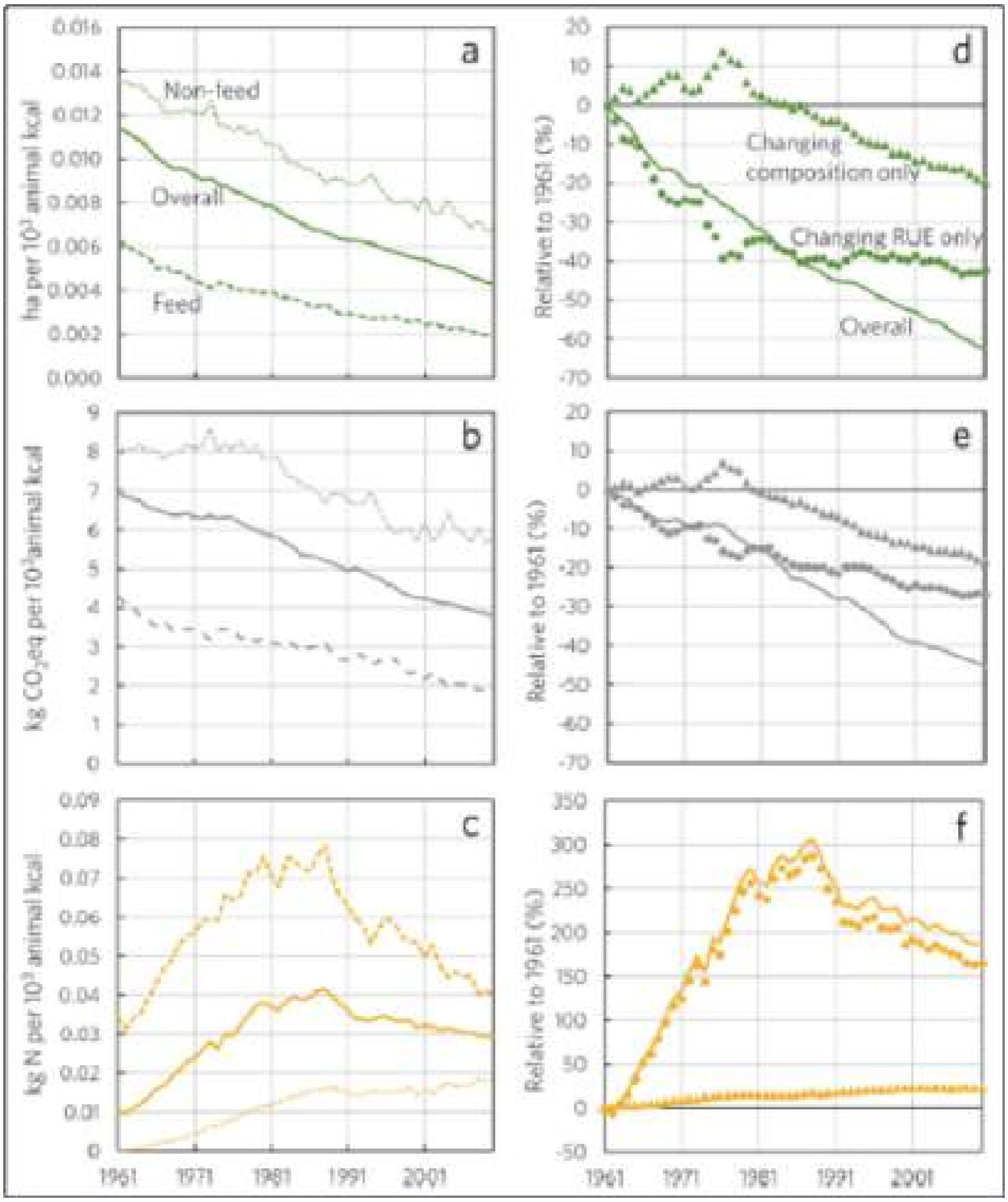


Figure S 5 Historical trends in land use, greenhouse gas emissions and nitrogen (N) use intensities of the livestock sector 1961-2010 (Davis et al., 2015).



This Report was prepared by members of the Scientific Group and members of its Research Partners.

Stanford University | Stockholm Resilience Centre | Stockholm University | EAT

The Blue Food Assessment

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by the Scientific Group for the Food Systems Summit
July 2021

THE VITAL ROLES OF BLUE FOODS IN THE GLOBAL FOOD SYSTEM

by Jim Leape, Fiorenza Micheli, Michelle Tigchelaar, Edward H. Allison, Xavier Basurto, Abigail Bennett, Simon R. Bush, Ling Cao, Beatrice Crona, Fabrice DeClerck, Jessica Fanzo, Stefan Gelcich, Jessica A. Gephart, Christopher D. Golden, Christina C. Hicks, Avinash Kishore, J. Zachary Koehn, David C. Little, Rosamond L. Naylor, Elizabeth R. Selig, Rebecca E. Short, U. Rashid Sumaila, Shakuntala H. Thilsted, Max Troell and Colette C.C. Wabnitz

ABOUT THE AUTHORS

Blue foods in food system decision-making

James P. Leape, Center for Ocean Solutions, Stanford University
Abigail Bennett, Dept. of Fisheries and Wildlife, Michigan State University
Beatrice Crona, Stockholm Resilience Centre
Fabrice DeClerck, EAT Forum and One CGIAR
Jessica Fanzo, Berman Institute of Bioethics, Johns Hopkins University
Jessica A. Gephart, Dept. of Environmental Science, American University
Avinash Kishore, International Food Policy Research Institute
Rosamond L. Naylor, Center on Food Security and the Environment, Stanford University
Elizabeth R. Selig, Center for Ocean Solutions, Stanford University
U. Rashid Sumaila, Institute for the Oceans and Fisheries, University of British Columbia; School of Public Policy and Global Affairs, University of British Columbia
Max Troell, Stockholm Resilience Centre

Blue foods to combat malnutrition

Michelle Tigchelaar, Center for Ocean Solutions, Stanford University
Christopher D. Golden, Department of Nutrition, Harvard T.H. Chan School of Public Health
Christina C. Hicks, Lancaster Environment Centre, Lancaster University
J. Zachary Koehn, Center for Ocean Solutions, Stanford University
Shakuntala H. Thilsted, WorldFish, CGIAR
Colette C.C. Wabnitz, Center for Ocean Solutions, Stanford University; Institute for the Oceans and Fisheries, University of British Columbia

Supporting small-scale actors in blue food value chains

Fiorenza Micheli, Center for Ocean Solutions, Stanford University; Hopkins Marine Station, Stanford University
Edward H. Allison, WorldFish, CGIAR
Xavier Basurto, Nicholas School of the Environment, Duke University
Simon R. Bush, Environmental Policy Group, Wageningen University
Ling Cao, School of Oceanography, Shanghai Jiao Tong University
Christina C. Hicks, Lancaster Environment Centre, Lancaster University
Stefan Gelcich, Instituto Milenio en Socio-ecologia Costera & Center of Applied Ecology and Sustainability, Pontificia Universidad Catolica de Chile
David C. Little, Institute of Aquaculture, University of Stirling
Rebecca E. Short, Stockholm Resilience Centre

EXECUTIVE SUMMARY

Blue foods – fish, invertebrates, algae and aquatic plants captured or cultured in freshwater and marine ecosystems – play a central role in food and nutrition security for billions of people and are a cornerstone of the livelihoods, economies, and cultures of many coastal and riparian communities. Blue food systems are extraordinarily diverse, involving thousands of species in many different production systems and supporting a wide array of cultures and diets, including those of Indigenous Peoples. Many blue foods are rich in bioavailable micronutrients and can be produced in ways that are more environmentally sustainable than terrestrial animal-source foods. Nonetheless, despite their unique value and interconnections with terrestrial food systems, blue foods are often left out of food system analyses, discussions, decisions, and solutions.

Realizing the potential of blue foods to play a central role in ending malnutrition and in building healthy, nature-positive and resilient food systems will require that governments embed blue foods in food system governance. Here, we focus on three central imperatives for policy-makers.

1. Bring blue foods into the heart of food system decision-making.

Governments should integrate blue foods into food policy-making, for example in a Ministry of Food, so that they can govern the entire food value chain, from producers to consumers, for both terrestrial and aquatic systems. They should ensure that blue foods are managed as a food system, not just a natural resource, for human sustenance and within environmental limits, and that they are fully included in policies for the food system as a whole.

2. Protect and develop the potential of blue foods to help end malnutrition.

Governments should recognize the right to food and manage blue foods as a source of nutrients that can help end malnutrition. To that end, food policy should harness the nutritional diversity of blue foods; take measures across the food system to reduce loss of nutrients from waste, environmental change and management failures; and ensure equitable distribution of blue food production and consumption.

3. Support the central role of small-scale actors in fisheries and aquaculture.

Small-scale actors supply most of the blue food for human consumption. Governments need to ensure they – including women, Indigenous Peoples and other historically marginalized groups – are included in blue food decision-making and policy. Government policy should expand investment in small-scale actors, support sustainable development and diversification of their sector, and ensure that trade and economic policy takes account of their roles in providing equitable economic opportunity and nutrition.

INTRODUCTION

Debates and decisions about food systems generally focus on agriculture and livestock. Blue foods – fish, invertebrates, algae and aquatic plants captured or cultured in freshwater and marine ecosystems – are perennially neglected[1]. Nonetheless, blue foods play a central role in food and nutrition security for billions of people and will be ever more important as the world seeks to create just food systems that support the health of people and the planet[2–6]. It is thus paramount that governments bring blue food systems into their food-related decision-making.

Last year, the UN Committee of World Food Security High Level Panel of Experts called for a transformation of the food system, moving "from a singular focus on increasing the global food supply through specialized production and export to making fundamental changes that diversify food systems, empower vulnerable and marginalized groups, and promote sustainability across all aspects of food supply chains, from production to consumption"[7]. Properly understood and managed, blue foods are profoundly suited to that shift.

The blue food portfolio is highly diverse. There are more than 3,000 species of marine and freshwater animals and plants used for food[6,8]. Blue food systems are supported by a wide range of ecosystems, cultures and production practices – from large-scale trawlers on the high-seas to small-scale fishponds integrated within agricultural systems – supporting access to nutritious food for communities through global and local markets alike. This diversity supports resilience that can help local food systems withstand shocks like COVID-19 and climate extremes[9–11] and offers many possibilities for governments and communities seeking to build food systems that are healthy, sustainable, and just.

Blue foods can be a cornerstone of good nutrition and health. Many of them are rich in bioavailable micronutrients that help prevent maternal and infant mortality, stunting, and cognitive deficits. And blue foods can be a healthier animal-source protein than terrestrial livestock: they are rich in healthy fats and can help reduce obesity and non-communicable diseases. In many parts of the world, blue foods are also more accessible and affordable than other animal-source foods[12,13]. Aquatic plants, including seaweeds, are a traditional presence in diets in the Asia-Pacific region and offer a variety of possibilities for low-carbon, nutritious food. Coastal and riparian Indigenous Peoples, from the Arctic to the Amazon, have traditionally had among the highest per capita aquatic food consumption rates in the world[14,15].

Blue foods can have lighter environmental footprints than other animal-source foods16. Across a diverse sector, the details matter: greenhouse gas emissions and biodiversity impacts can be quite high for some blue food systems, such as bottom trawling or aquaculture systems with low feed efficiencies, especially when they are poorly sited or poorly managed. However, many fisheries and aquaculture systems already offer footprints that are much lower than beef, with vast potential to be improved further[16]. In some cases, unfed aquaculture (such as filter-feeding shellfish and seaweeds) can actually improve the water quality of the environment it occupies.

Blue foods are important to livelihoods in many vulnerable communities. The FAO estimates that about 800 million people make their living in blue food systems[17], mostly in small-scale fisheries and aquaculture. These systems produce a wide variety of blue foods, supporting healthy diets and resilience in the face of climate change and market fluctuations.

To capitalize on the potential of blue foods, decision-makers must address significant challenges. Wild-capture fisheries, both marine and freshwater, need to be better managed[18,19] as many fish stocks have become severely depleted and some technologies have high environmental footprints. Although aquaculture is becoming increasingly sustainable, growing use of feed in some sectors is putting pressure on the environment through overfishing, deforestation for feed crops and intensification of agricultural production. Intensification of aquaculture can concentrate nutrient pollution and exacerbate risks associated with pathogens and high dependence on antibiotics[20].

Environmental stressors can also limit blue food production and must be mitigated. Climate change will increasingly affect the health and productivity of fish stocks and aquatic ecosystems[21]. These impacts will have implications for food security, livelihoods and economies worldwide and especially in wild-capture fisheries in Africa, East and South Asia, and small island developing states[22,23]. Other kinds of pollution, from agricultural runoff to plastics, further threaten productivity and the safety of foods harvested from polluted waters[24,25].

Like all food systems, blue food systems are beset by inequities. Wealth-generating activities are often favored over those important to nutrition and health, livelihoods, and culture. The aquatic resource management systems, knowledge and rights of Indigenous Peoples and traditional small-scale fisherfolk have often been undermined or overlooked in fisheries, water management and ocean governance[26]. Although blue food value chains employ roughly equal numbers of men and women4, their roles, influence over value chains, and benefits can be highly unequal. Progress towards gender equality is critical for development of more equitable and efficient blue food systems[5,27].

Blue foods are the most highly-traded food products: for developing countries, net revenues from trade of blue foods exceed those of all agricultural commodities combined[28–30]. However, global supply chains are complex and often opaque, making it difficult or impossible for buyers to ascertain environmental impacts and human rights abuses in production. In some places harvesting and trade of fish for high monetary value global markets have undermined production that is important for local food security and livelihoods[31].

There is every reason to expect that total demand for blue foods will grow substantially in the years ahead, as population and incomes increase, and as attention towards healthy and sustainable food expands. If produced responsibly, they have essential roles to play in ending malnutrition and in building healthy, nature-positive and resilient food systems, including for people living on lands marginal for agricultural production (particularly forests, wetlands and small islands), many of whom are Indigenous[32]. However, realizing that potential will require that governments are thoughtful about how to develop those roles. Here, we focus on three central imperatives for policy-makers:

1. Integrate blue foods into decision-making about food system policies, programs, and budgets, to enable effective management of production, consumption and trade, and the interconnections with terrestrial food production.
2. Understand, protect and develop their potential in ending malnutrition, fostering production of accessible, affordable nutritious foods.
3. Support the central role of small-scale actors, with governance and finance that are responsive to their diverse needs, circumstances and opportunities.

The Bangladesh Story

The proliferation of diverse, freshwater aquaculture supply chains in Bangladesh in recent decades illustrates the potential for blue foods to meet domestic demand, improve food and nutrition security, and reduce rural poverty[33]. This "hidden aquaculture revolution" has involved the participation of hundreds of thousands of small- to medium-scale actors along the supply chain, acting independently and in response to urbanization, growing incomes, and rising fish demand. Approximately 94% of the fish produced in freshwater aquaculture in Bangladesh is directed towards domestic markets and is not traded internationally. Although mostly small-scale, freshwater aquaculture systems have become increasingly intensive and commercial in their operations[34]. Aquaculture growth and its contribution to food and nutrition security in Bangladesh have resulted from public investment in infrastructure, a positive business environment for small- and medium-size entrepreneurs, and 'light touch' government control over the type of systems and species produced[33].

POLICY RECOMMENDATION 1: BRING BLUE FOODS INTO THE HEART OF FOOD SYSTEM DECISION-MAKING

The problem: Fisheries and aquaculture are typically ignored in management of food systems

Blue foods are deeply interconnected with the rest of the food system, in diets, in supply chains, and in the environment. Aquatic and terrestrial foods appear on the same plate and are often substitutes for each other in household food choices. Capture fisheries provide feed inputs for aquaculture and livestock; terrestrial crops provide feed inputs for aquaculture. Excess nutrients from agriculture and aquaculture pollute rivers and cause coastal dead zones, undermining fisheries; cultivation of filter-feeding fish and seaweeds takes up nutrients and, if properly managed and scaled, can help protect ecosystem health. Genetic advances in crops and livestock have had positive spillover effects on aquaculture through selection and breeding and through improvements in nutritional performance and feed efficiency.

Nonetheless, blue foods are generally ignored in food system discussions and decision-making1. Blue foods receive little attention in development assistance: the World Bank, the Bill and Melinda Gates Foundation and other major development funders have largely neglected the roles of fish, shellfish and aquatic plants in human nutrition and health. Blue foods also tend to be left out of food system policy-making at the national level. Ministries or agencies dedicated to capture fisheries and aquaculture tend to manage them as a natural resource, with a focus on economic interests, namely production and trade. In many countries, the result is that both fisheries and aquaculture are managed with an emphasis on high monetary value, export-oriented production. That orientation is reinforced by the market and naturally favors investments in innovations and enterprises that offer the highest financial return. Critical welfare functions are often neglected; indeed, fisheries agencies often lack the mandate to address the potential contributions of blue foods to food security and public health, livelihoods and communities, and cultural traditions and diets.

When fisheries and aquaculture are siloed and managed as a natural resource, policy-makers miss vital opportunities for advancing their goals for nutrition, sustainability, resilience, and livelihoods, and they make unwitting trade-offs among those interests. Fisheries that have sustained communities for generations are depleted by distant water fleets or outcompeted in the market by large volumes of inexpensive farmed

The African Great Lakes

The small pelagic fisheries of the African Great Lakes region illustrate the opportunities in bringing blue foods into food system policy-making. These fisheries produce huge volumes of affordable, micronutrient-rich food traded throughout the region, but they have been given low priority for investment and management because they are seen as having low economic value. Food system policy-making approaches could include investments to a) reduce post-harvest loss, which can be substantial, and improve food quality and safety; b) strengthen domestic and intra-regional trade institutions to enhance small-scale trader market access; c) address challenges, risks and opportunities of female fish traders, who comprise a substantial portion of the post-harvest sector, and d) manage trade-offs between sale for animal feed industries and direct human consumption.

fish. Farming of species that could remedy pressing nutrient deficiencies remains undeveloped because management and investment are directed to high-revenue products. Small-scale producers who are central to local diets, livelihoods and community resilience lose out to large commercial concessions.

The solution: Governments should fully integrate blue foods into their governance of the food system

The potential of blue foods will only be realized if they are brought into food system decision-making. That requires integrated governance, systematic inclusion in policy, and a basic change in the way we think about fish. Specifically, governments should:

1. Create a governance structure that integrates green and blue

Governments should create a Ministry of Food or other structure that can govern the entire food system, managing synergies and trade-offs in production, consumption and trade. Ministries of agriculture and of fisheries typically focus on production – generally on increasing volume – and often are captured by entrenched interests. A Ministry of Food or similar entity could manage the disparate interests of producers, consumers, and other stakeholders for improved nutritional, environmental, economic, and social outcomes. It could, for example, manage production and consumption to create markets for more nutritious species (see Section 2). It could also expand the capabilities of small-scale producers, through investment and allocation of resource rights to support livelihoods and community resilience (see Section 3). More broadly, it enables decision-makers to govern blue foods as a food system, and ensure that blue foods are fully included in all food system policies.

2. Govern blue foods as a food system

At the most basic level, integrating blue foods into food system decision-making also recognizes that fisheries and aquaculture should themselves be managed as food systems: they should be managed to deliver society's goals for nutrition, health and equity, as well as for economics and sustainability. Government policy and management should embrace all aspects of the blue food sector, including fisheries, aquaculture development, distribution, exports and imports, and consumption.

Promoting a systems approach means that governments can ensure nutrient-rich aquatic foods are available and affordable to those for whom they are most important, both nutritionally and culturally. It can work across the value chain to identify and address the many threats to supply of blue foods, from overfishing to pollution to waste and loss in harvesting, processing and distribution (see Section 2). It can build a system that is just, ensuring equitable participation in production, accessibility for consumption, and broad representation in decision-making. By managing blue foods as a system, governments can also create policies and incentives across the value chain to shift both production and consumption to species and technologies that have lighter footprints and foster diversity in production systems.

Looking at the whole system also enables the government to make public investments where markets fail. Private investment goes to blue food systems and enterprises that offer high financial returns. Governments can allocate public funds to develop innovations in fisheries and aquaculture that offer lower returns but are important for nutrition, livelihoods, and sustainability, and it can provide capital for small and medium-sized enterprises to take those innovations to scale.

To realize this vision, governments will need to collect data that enable good decisions, including data that enable monitoring of fisheries and supply chains, that capture the vital diversity of species that are produced and consumed, that survey the demographic diversity of participants in the sector, and that reflect the frequently profound heterogeneity in consumption across different regions of the country and between different ethnic and religious groups. They will also need to redesign policies to enable and incentivize the capabilities of key actors – from producers to consumers – to adopt transformative practices in the food system as a whole, in value chains, and in the places where they live (see Section 3).

3. Include blue foods in all food system policies

Structural reform must be followed by policy inclusion, whereby governments should integrate blue foods into the policies that regulate, guide and support the food sector. Government strategies to meet the human right to food, for example (see Section 2), should embrace the potential of blue foods to offer accessible, affordable sources of key nutrients. Dietary guidelines should include the nutritional contributions of different blue foods, to help consumers understand their value for addressing nutrient deficiencies and obesity, diabetes and coronary disease. Safety net programs for children and pregnant and lactating women should also include blue foods, as fish can be a rich source of essential micronutrients for those most vulnerable populations, helping to prevent stunting and cognitive deficits. The food systems and food sovereignty of Indigenous Peoples must be supported.

Including blue foods in policy-making for the food system allows governments to better manage the interconnections between terrestrial and aquatic food systems. That includes the regulation of agricultural and inland aquaculture runoff and other land-based pollution that can undermine coastal fisheries and marine aquaculture, such as nutrients that cause coastal dead zones and toxins that can compromise food safety. Governments can also better manage the allocation of crops and fish to competing uses – for food or feed – and support the development of a circular economy in which wastes or by-products from one part of the food system are used as feed inputs to another.

POLICY RECOMMENDATION 2: PROTECT AND DEVELOP THE POTENTIAL OF BLUE FOODS TO HELP END MALNUTRITION

The problem: Blue food systems are not managed for nutrition

Many blue foods contain high concentrations of bioavailable minerals and vitamins, essential fatty acids, and animal protein[8]: globally roughly 8% of zinc and iron, 13% of protein, and 27% of vitamin B12 are derived from aquatic foods[6]. Blue foods can therefore make key contributions to diet-related health challenges. They can reduce micronutrient deficiencies that lead to disease; improve heart, brain and eye health by uniquely providing omega-3 fatty acids; and replace consumption of less healthy red and processed meats[6]. The micronutrient contributions of blue foods are especially important for childhood development, pregnant women and women of childbearing age[35–37] and can reduce nutritional inequities for girls and women[6].

Not all fish are equal. For example, a single serving of small indigenous species in Bangladesh, eaten whole, contributes more than five times as much vitamin B12 as a single serving of tilapia fillet8. Which blue foods are on a plate and in what form therefore matters as well as the quantity[6,31]. Nonetheless, blue food policy often only considers blue foods as a protein source, which neglects the nutrient diversity of fish (in terms of micronutrients and fatty acids) and excludes the contributions of aquatic plants altogether. In the Bangladesh case discussed above, for example, growth in (farmed) fish consumption has led to an increase in total protein consumption but a decrease in consumption of certain micronutrients, highlighting the challenge of balancing high nutrient content provided by small native fish with employment and revenue generation offered by tilapia and pangasius production[38]. Adopting a nutrition-sensitive approach to aquaculture and fisheries, rather than just a production-focus, can address these issues[1,8,39].

In many countries, ministries manage blue foods for their wealth-generating benefits, focusing policy on high economic value blue food production, often for export. Such a focus risks undermining the critical welfare functions of blue foods by neglecting the nutritional characteristics, livelihood contributions, accessibility, and cultural patterns of blue food consumption[1,5,8,31]. Nutrient-dense blue foods are regularly exported from nutritionally vulnerable countries to either serve as a high-quality product for wealthy consumers or be reduced to fishmeal to feed farmed fish for high-income countries[40]. Orientation towards export markets not only affects coastal and riparian populations, but also inland communities who have historically depended on richly nutritious dried or smoked fish transported from the coast[41].

The quantity, quality and safety of blue food supply are threatened by waste (amounting to 35% of fish harvested globally[4]), management failures (including overfishing and Illegal, Unreported, and Unregulated fishing), environmental degradation, and climate change[21]. It is estimated that declines in marine fish catch over the next three decades could subject an additional 845 million people (11% of the world's population) to vitamin A, zinc, or iron deficiencies[23]. Although all of these pressures occur globally, their effects are highest and most strongly felt in tropical and low-income countries with high dependence on blue foods for nutrition and health, livelihoods and income[22,23].

Finally, blue food policy misses opportunities to support nutrition goals when it fails to address unequal distribution of the benefits from blue food systems or the concentration of power. Women in particular are underrepresented in policies and decision-making[5,27,42]. Where gender equality is lacking, blue foods are less affordable[5] and blue food waste and losses are greater[43].

The solution: Sustain and enhance the nutritional benefits of blue food systems

To manage blue food systems for the benefit of nutrition and health, governments should:

1. Recognize the centrality of the right to food in blue food trade and domestic policy

The right to food states that everyone is entitled to adequate, accessible, and safe food, that corresponds to their cultural traditions in a fulfilling and dignified manner[44]. A right to food means that governance of and investment in blue food systems should seek balance between economic opportunities and local rights to food provisioning[1,5], aiming to sustain and innovate with the full diversity of species, production and harvest methods, product forms and distribution channels in mind[6]. Recognizing the right to food requires taking a food systems approach in which nutrition, sustainability, climate-resilience and equity can be considered together (see Section 1) and which ensures all actors are represented, including through engagement with grass-roots and civil society organizations (see Section 3)[1,5]. Recognizing the food rights of Indigenous Peoples who harvest aquatic foods is of particular importance, whether such peoples have nation status or not. At a national level, blue foods should explicitly be included in food and nutrition policy (see Section 1)[1,8]. Internationally, blue foods should be positioned as a vital food source in the context of the UN Sustainable Development Goals, health national adaptation plans (HNAPs), and other international efforts to alleviate malnutrition[1].

2. Harness the nutritional diversity of blue foods

Governments should ensure that the nutritional potential of blue foods serves to improve the health and diets of nutritionally vulnerable people. They should recognize and harness the diversity of local blue food nutritional profiles, preparation methods and dietary practices[19].

Governments should manage capture fisheries to optimize for nutritional benefits, not just for maximum sustainable yield, which can uncover opportunities to diversify fish production without increasing pressure on existing stocks[6,45]. Aquaculture development should foster the sustainable production of native small fish species that can supply context-specific nutrient needs. As an example, mola, a fish species from the Gangetic floodplains, can easily be produced in homestead ponds and offers 80 times more vitamin A than commonly farmed silver carp[8].

Governments should evaluate exports and licenses to distant water fleets to ensure that they do not compromise nutritional goals. In some cases (e.g. Namibia) retaining just a small portion of current exports could meet local nutrition goals[31], although this requires infrastructure to support equitable distribution and access to blue foods locally (see Section 3).

Public health policies and investments focused on reducing malnutrition should include blue foods in programs to address the specific nutritional needs of pregnant and lactating women, young children and the elderly – with appropriate consideration of food safety and pollutants – as was done with the introduction of dried small fish powder in Myanmar to support children's health[46].

3. Halt loss of nutrients from blue food systems

To ensure that blue foods important for nutrition are available, accessible, and affordable, governments should take steps to reduce losses in the system. Improved processing methods can preserve and concentrate nutrients and increase availability and also improve nutritional quality[47].

In many places, better management of capture fisheries through harvest controls or spatial restrictions, for example, can restore fish stocks and increase yields[18,19,48]. Better regulation of economic development in floodplains, riparian, coastal, and ocean ecosystems can help protect blue food production and reduce risks to food safety[49,50].

Fisheries and aquaculture policy should also anticipate and adapt to projected climate change[21,22]. Governments should consider nature-based solutions like mangrove and seagrass restoration and restorative aquaculture that can help strengthen the resilience of aquatic ecosystems[51,52]. Additional climate adaptation options are context-specific but include shifting to offshore resources[53], devising climate-smart agreements for transboundary resources[54] and investing in climate information systems, including early warning systems for extreme events[55,56]. Place-based responses to climate change are particularly important for Indigenous Peoples whose cultures and identities are closely linked to their local environments[57].

4. Improve the distributional equity of blue food production and consumption

Participation in activities along the value chain is often socially differentiated; for example, men dominate blue food production and women blue food processing. Governments thus need to collect data on what roles, from fish producers to post-harvest processors, traders, and consumers, different groups in society hold and why. When divisions of labor exist because of unequal opportunities to participate across the value chain, they are likely to result in distributional and nutritional inequities[42]. Investments to address the drivers of unequal opportunities, such as through strengthening women's empowerment, are known to lead to improvements in outcomes for women and their families. For example, in Zambia, strategies to uncover underlying structural barriers that limit participation, such as unequal norms and attitudes, increased women's participation in production processes, and their control over resources[43]. Governments need to ensure the full diversity of actors, across social groups, including gender, class, and ethnicity, and along the value chain and scale of production, are fairly represented in decision-making processes[5] (see Section 3). In addition, governments should recognize subnational differences in nutritional vulnerability and blue food access in national policy and align subnational policies and instruments with nutritional goals.

Policy recommendation 3: Support the central role of small-scale actors in fisheries and aquaculture

The problem: Limited recognition and support for the small-scale fisheries and aquaculture sector in supporting equitable and sustainable food systems

Small-scale fisheries and aquaculture (SSFA) have been marginalized in dialogues about sustainable and equitable food system transformation, despite being central to it in many contexts[1]. SSFA play a key role in supplying nutrition and supporting local economies in many countries. They produce more than half of the global fish catch and contribute over two-thirds of aquatic foods destined for direct human consumption[4], with the potential for lower environmental footprints (e.g. lower fuel use than in large-scale operations[16]). In addition, the value chains that process and sell their products support about 800 million full- and part-time jobs, half of which are women[4,17]. SSFA produce a high diversity of aquatic foods. This diversity underpins healthy diets, and resilience in the face of shocks, climate and market changes[31,39,58,59]. SSFA also contribute to intra-regional trade, especially in smoked and dried products, which can have more direct impacts on food security and poverty alleviation than the globalized system[60].

SSFA worldwide face a growing range of threats and challenges, including resource over-exploitation, habitat degradation, poor political representation, market-driven competition for resources (e.g. patterns of trade and foreign fishing), assumed links between informality and illegality[61], climate change[62], and shocks such as the current COVID-19 pandemic[58,63,64]. Cumulatively, SSFA are being 'squeezed out' of the spaces they occupy on the land-water margins by other more powerful sectors, such as tourism, residential and industrial land use, oil and gas exploration, industrial fisheries and aquaculture[65]. Within SSFA, inequitable access to resources and opportunities and limited gender and social inclusion are key threats. Indigenous Peoples whose lands and waters have been colonized by others, and whose harvesting activities tend to be small-scale, continue to be marginalized by public policy. Finally, pervasive data and monitoring limitations pose major challenges to understanding the status of SSFA[66] as a lack of data leads to underestimating SSFA contributions, marginalizing SSFA in policy and decision-making, and aggregated and categorical data fail to represent the diversity of SSFA actors and benefits.

Governments and policies predominantly focus on industrialized, large-scale fisheries and aquaculture, leading to a lack of voice and support for SSFA. One reason for this persistent neglect is that policy-makers struggle with the diversity, dynamism and perceived informality of SSFA and their associated cultures[5]. Most policies affecting the sector make unrealistic assumptions that SSFA are a homogenous group limited to producers[67,68]. In contrast, the sector is extraordinarily diverse along many dimensions[64]. Successful transformations of SSFA require supporting current activities, while exploring new opportunities and encouraging both the entry of new actors into the sector and the redeployment of some current actors to opportunities outside it.

The solution: Support SSFA capabilities and diversity through inclusive blue food policy

Governments of countries where SSFA operate should place this sector at the center of their national human development and food security strategies, creating initiatives that support the capabilities of the diverse SSFA actors. Supporting the viability of SSFA requires governments to:

1. Include actors from SSFA in decision-making and policy development

Inclusion of SSFA in decision-making is essential to enable more adaptive governance mechanisms and policies that build on the strengths of the diversity of SSFAs, acknowledge the cultural importance and specific roles of blue foods for diverse actors and steer food systems towards a more equitable distribution of blue food benefits.

Women are greatly underrepresented in policy and decision-making even though they make up half of the workforce in SSFA globally. Recent efforts to improve gender equity in blue food policy have tended to adopt a narrow focus on women, overlooking men or gender relations[27]. Such a narrow focus risks exacerbating inequities by placing the blame, or burden for change, on women[5]. Blue food policy development therefore not only needs to involve more input and leadership from women, but also should take a gender transformative approach to improving intersectional equity in SSFA[5,27,69].

Indigenous coastal and riparian peoples tend to be more blue food-dependent than the wider population in the countries they live in[14,15]. They also have proven systems for food system governance – including knowledge systems – that, if recognized and supported, could enable the 'decolonization' of their food systems[70]. As access to traditional food sources has been lost, adoption of unhealthy diets based on processed foods have led to high rates of diet-related non-communicable diseases[71,72]. Thus, by supporting Indigenous Peoples food (and wider) sovereignty claims, governments could contribute to transformative health benefits in these communities and nations.

Governments should support and strengthen multi-stakeholder initiatives that have the benefits of SSFA at their core, including organizations of fish workers, harvesters and producers at global, regional, and national levels such as the World Forum of Fish Harvesters and Fishworkers (WFF), the World Forum of Fisher Peoples (WFFP), and the International Collective in Support of Fish Workers (ICSF).

2. Expand capabilities through investment in institutions and human capital, and investment in environmental protection and restoration

Securing the future of SSFA requires adaptive action that supports the capabilities of SSFA to deliver both market and non-market societal benefits. Positive environmental outcomes, for example, require engagement of SSFA actors to co-produce knowledge, forge strategies for sustainability and climate adaptation, and participate in and lead environmental restoration, conservation and adaptation efforts.

Governments should create space for SSFA as they expand agricultural, and industrial aquaculture and fisheries sectors. They should use public and private regulation and financial mechanisms to enable SSFA actors – including Indigenous Peoples – to (re)gain control over the resources, rights, skills and knowledge necessary for environmentally resilient and socially equitable production and trade (including insurance, credit, and market mechanisms to buffer against extreme events).

Governments should also allocate and enforce land, water and labor rights to SSFA through user rights-based systems, creation of preferential access areas, coastal and inland land use zoning, or other measures. To support the roles of SSFA in creating livelihoods and resilient and equitable food systems, governments should also provide capital, through public and private financial mechanisms that empower rather than undermine SSFA actors. In the case of Indigenous Peoples, recognition of their collective sovereign rights is the key starting point.

3. Support diversification and sustainable intensification

For many SSFA producers, it will be crucial to find pathways for sustainable intensification or expansion of their operations or for diversification into other SSFA products or other sources of livelihood. To that end, governments should invest in R&D and facilitate access to venture capital to support innovation in species/production systems that are of high value for nutrition, livelihoods, and justice. They should also support the development of complementary livelihoods, which are often critical to continued participation by SSFA actors, their control of the resource base and its sustainability.

Costs, trade-offs, and potential environmental and social impacts of intensification and diversification should be carefully considered, and diversification should be proactively designed and monitored. To this end, efforts should be made towards better integration of different data types and sources and enabling the effective and timely access and use of data by relevant actors. Investment is needed in monitoring systems for catch, effort, production and consumption, and in national surveys of engagement in SSFA which are fully gender-inclusive, and reflect intersections of gender, age and ethnicity. Promotion of R&D towards technological solutions to data collection, storage and communication/accessibility barriers would effectively support these needs.

4. Secure economic and nutritional benefits through trade policies and the development and protection of local and national markets

Governments, in particular low-income food insecure nations, need to be able to regulate the activities of large corporate actors and trade to protect the rights (e.g. labor rights, human rights, right to food) of SSFA workers, to ensure that terms, conditions, and revenues from trade are transparent and fair, do not impact on local food security, and where needed retain high nutritional value products for local consumption. Regulation should consider the potential trade-offs and linkages between nutritional and economic value of resources. It should establish transparent processes, monitoring systems, and accountability mechanisms to ensure traceability and visibility of social impacts. Market-based approaches that encourage actors to add value to products through processing, marketing or certification need to carefully consider trade-offs in economic, social, environmental, and public health outcomes (see Section 1).

Governments should also explore opportunities to support "alternative" systems based on short supply chains for products with strong local identities and local, decentralized production and processing. Diversity, deeply embedded in these food systems, could be supported by policies mandating or incentivizing local retention of SSFA products to ensure food self-sufficiency, for example, the development or control of local markets and school feeding programs.

CONCLUSION

Blue foods have vital roles to play in transformation of the global food system. In the face of growing challenges and rising demand, governments must act now to support and expand these roles. They should bring blue foods into the heart of their food decision-making, by creating a Ministry of Food or other governance structures that integrate blue foods fully into food policies, budgets and programs, managing the terrestrial and aquatic food systems as a whole. They should recognize the right to food and harness the nutritional diversity of blue foods in ways that ensure the equitable distribution of blue food production and consumption. And they should empower and support the millions of small-scale actors in fisheries and aquaculture who produce, process, distribute and trade most of the food we eat, and can be the key to a vibrant, sustainable, healthy, and equitable blue food economy. Recognizing and acting upon the potential role of blue foods in all dimensions of food policy would be a clear win for the 2021 UN Food Systems Summit.

REFERENCES

1. Bennett, A. et al. Recognize fish as food in policy discourse and development funding. Ambio (2021) doi:10.1007/s13280-020-01451-4.
2. HLPE. Sustainable fisheries and aquaculture for food security and nutrition. http://www.fao.org/3/a-i3844e.pdf (2014).
3. Bennett, A. et al. Contribution of Fisheries to Food and Nutrition Security: Current Knowledge, Policy, and Research. (2018).
4. FAO. The State of World Fisheries and Aquaculture 2020. Sustainability in Action. http://www.fao.org/3/ca9229en/ca9229en.pdf (2020) doi:10.4060/ca9229en.
5. Hicks, C. C. et al. Towards justice in blue food systems. Nature.
6. Golden, C. D. et al. Aquatic foods for nourishing nations. Nature (in review).
7. HLPE. Impacts of COVID-19 on food security and nutrition: developing effective policy responses to address the hunger and malnutrition pandemic. http://www.fao.org/3/cb1000en/cb1000en.pdf (2020) doi:10.4060/cb1000en.
8. Thilsted, S. H. et al. Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61, 126–131 (2016).
9. Troell, M. et al. Does aquaculture add resilience to the global food system? Proc. Natl. Acad. Sci. U. S. A. 111, 13257–13263 (2014).
10. Béné, C. Resilience of local food systems and links to food security - A review of some important concepts in the context of COVID-19 and other shocks. Food Secur 1–18 (2020).
11. Love, D. C. et al. Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. Global Food Security 28, 100494 (2021).
12. Ryckman, T., Beal, T., Nordhagen, S., Chimanya, K. & Matji, J. Affordability of nutritious foods for complementary feeding in Eastern and Southern Africa. Nutr. Rev. 79, 35–51 (2021).
13. Ryckman, T., Beal, T., Nordhagen, S., Murira, Z. & Torlesse, H. Affordability of nutritious foods for complementary feeding in South Asia. Nutr. Rev. 79, 52–68 (2021).
14. Bayley, P. B. Fish Yield from the Amazon in Brazil: Comparison with African River Yields and Management Possibilities. Trans. Am. Fish. Soc. 110, 351–359 (1981).
15. Cisneros-Montemayor, A. M., Pauly, D., Weatherdon, L. V. & Ota, Y. A Global Estimate of Seafood Consumption by Coastal Indigenous Peoples. PLoS One 11, e0166681 (2016).

16. Gephart, J. A. et al. Environmental performance of blue foods. Nature (in review).
17. FAO Fisheries and Aquaculture Department. The State of World Fisheries and Aquaculture 2012. http://www.fao.org/3/i2727e/i2727e.pdf (2012).
18. Hilborn, R. et al. Effective fisheries management instrumental in improving fish stock status. Proc. Natl. Acad. Sci. U. S. A. 117, 2218–2224 (2020).
19. Melnychuk, M. C. et al. Identifying management actions that promote sustainable fisheries. Nature Sustainability 1–10 (2021).
20. Naylor, R. L. et al. A 20-year retrospective review of global aquaculture. Nature 591, 551–563 (2021).
21. FAO. Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options. vol. 627 (2018).
22. Tigchelaar, M. et al. Compound climate risk threatens aquatic food system benefits. Nature Food.
23. Golden, C. D. et al. Nutrition: Fall in fish catch threatens human health. Nature 534, 317–320 (2016).
24. Bank, M. S., Metian, M. & Swarzenski, P. W. Defining Seafood Safety in the Anthropocene. Environ. Sci. Technol. 54, 8506–8508 (2020).
25. Garrido Gamarro, E., Ryder, J., Elvevoll, E. O. & Olsen, R. L. Microplastics in Fish and Shellfish – A Threat to Seafood Safety? J. Aquat. Food Prod. Technol. 29, 417–425 (2020).
26. Ratner, B. D., Åsgård, B. & Allison, E. H. Fishing for justice: Human rights, development, and fisheries sector reform. Glob. Environ. Change 27, 120–130 (2014).
27. Lawless, S., Cohen, P. J., Mangubhai, S., Kleiber, D. & Morrison, T. H. Gender equality is diluted in commitments made to small-scale fisheries. World Dev. 140, 105348 (2021).
28. Gephart, J. A. & Pace, M. L. Structure and evolution of the global seafood trade network. Environ. Res. Lett. 10, 125014 (2015).
29. Sumaila, U. R., Bellmann, C. & Tipping, A. Fishing for the future: An overview of challenges and opportunities. Mar. Policy 69, 173–180 (2016).
30. FAO. FAO Yearbook. Fishery and Aquaculture Statistics 2018/FAO annuaire. Statistiques des pêches et de l'aquaculture 2018/FAO anuario. Estadísticas de pesca y acuicultura 2018. http://dx.doi.org/10.4060/cb1213t (2020) doi:10.4060/cb1213t.
31. Hicks, C. C. et al. Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574, 95–98 (2019).
32. Azam-Ali, S. et al. Marginal areas and indigenous people: Priorities for research and action. (2021).
33. Hernandez, R. et al. The "quiet revolution" in the aquaculture value chain in Bangladesh. Aquaculture 493, 456–468 (2018).
34. Belton, B., Bush, S. R. & Little, D. C. Not just for the wealthy: Rethinking farmed fish consumption in the Global South. Global Food Security 16, 85–92 (2018).
35. Kawarazuka, N. & Béné, C. The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. Public Health Nutr. 14, 1927–1938 (2011).
36. Bogard, J. R. et al. Inclusion of Small Indigenous Fish Improves Nutritional Quality During the First 1000 Days. Food Nutr. Bull. 36, 276–289 (2015).
37. Starling, P., Charlton, K., McMahon, A. T. & Lucas, C. Fish intake during pregnancy and foetal neurodevelopment--a systematic review of the evidence. Nutrients 7, 2001–2014 (2015).
38. Bogard, J. R. et al. Higher fish but lower micronutrient intakes: Temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. PLoS One 12, e0175098 (2017).
39. Gephart, J. A. et al. Scenarios for global aquaculture and its role in human nutrition. Rev. fish. sci. aquac. 29, 122–138 (2021).
40. Isaacs, M. The humble sardine (small pelagics): fish as food or fodder. Agriculture & Food Security 5, 27 (2016).
41. Gordon, A., Finegold, C., Crissman, C. C. & Pulis, A. Fish Production, Consumption, and Trade in Sub-Saharan Africa: A Review Analysis. https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/884/WF-3692.pdf?sequence=1&isAllowed=y (2013).
42. Udo, I. U. & Okoko, A. C. Seafood processing and safety: A veritable tool for transformation and empowerment of rural women in Nigeria. Nigerian Journal of Agriculture, Food and Environment 10, 8–17 (2014).
43. Kaminski, A. M. et al. Fish Losses for Whom? A Gendered Assessment of Post-Harvest Losses in the Barotse Floodplain Fishery, Zambia. Sustain. Sci. Pract. Policy 12, 10091 (2020).
44. Fakhri, M. The right to food in the context of international trade law and policy. https://undocs.org/A/75/219 (2020).
45. Bernhardt, J. R. & O'Connor, M. I. Aquatic biodiversity enhances multiple nutritional benefits to humans. Proc. Natl. Acad. Sci. U. S. A. 118, (2021).
46. Dried small fish powder provides opportunity for child health in Myanmar. WorldFish Blog http://blog.worldfishcenter.org/2020/11/dried-small-fish-powder-provides-opportunity-for-child-health-in-myanmar/ (2020).
47. Siddhnath et al. Dry Fish and Its Contribution Towards Food and Nutritional Security. Food Rev. Int. 1–29 (2020).
48. Anderson, C. M. et al. How commercial fishing effort is managed. Fish Fish 20, 268–285 (2018).

49. Niane, B. et al. Human exposure to mercury in artisanal small-scale gold mining areas of Kedougou region, Senegal, as a function of occupational activity and fish consumption. Environ. Sci. Pollut. Res. Int. 22, 7101–7111 (2015).
50. de Oliveira Estevo, M. et al. Immediate social and economic impacts of a major oil spill on Brazilian coastal fishing communities. Mar. Pollut. Bull. 164, 111984 (2021).
51. Gattuso, J.-P. et al. Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Frontiers in Marine Science 5, 337 (2018).
52. Hoegh-Guldberg, O. et al. The ocean as a solution to climate change: Five opportunities for action. http://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf (2019).
53. McDonald, J. & Torrens, S. M. Governing Pacific fisheries under climate change. in Research Handbook on Climate Change, Oceans and Coasts (Edward Elgar Publishing, 2020).
54. Oremus, K. L. et al. Governance challenges for tropical nations losing fish species due to climate change. Nature Sustainability 1–4 (2020).
55. Cinner, J. E. et al. Building adaptive capacity to climate change in tropical coastal communities. Nat. Clim. Chang. 8, 117–123 (2018).
56. Turner, R., McConney, P. & Monnereau, I. Climate Change Adaptation and Extreme Weather in the Small-Scale Fisheries of Dominica. Coast. Manage. 48, 436–455 (2020).
57. Whitney, C. et al. "Like the plains people losing the buffalo": perceptions of climate change impacts, fisheries management, and adaptation actions by Indigenous peoples in coastal British Columbia, Canada. Ecol. Society 25, 33 (2020).
58. Bennett, N. J. et al. The COVID-19 Pandemic, Small-Scale Fisheries and Coastal Fishing Communities. Coast. Manage. 1–11 (2020).
59. Campbell, S. J. et al. Immediate impact of COVID-19 across tropical small-scale fishing communities. Ocean Coast. Manag. 200, 105485 (2021).
60. Béné, C., Lawton, R. & Allison, E. H. "Trade Matters in the Fight Against Poverty": Narratives, Perceptions, and (Lack of) Evidence in the Case of Fish Trade in Africa. World Dev. 38, 933–954 (2010).
61. Song, A. M. et al. Collateral damage? Small-scale fisheries in the global fight against IUU fishing. Fish Fish 21, 831–843 (2020).
62. Monnier, L. et al. Small-scale fisheries in a warming world: Exploring adaptation to climate change. (2020).
63. Farmery, A. K. et al. Blind spots in visions of a "blue economy" could undermine the ocean's contribution to eliminating hunger and malnutrition. One Earth 4, 28–38 (2021).
64. Short, R. E. et al. Harnessing diversity of small-scale actors key to aquatic food futures. Nature Food (in review).
65. Cohen, P. et al. Securing a Just Space for Small-Scale Fisheries in the Blue Economy. Frontiers in Marine Science 6, 171 (2019).
66. Pauly, D. & Zeller, D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat. Commun. 7, 10244 (2016).
67. Gelcich, S., Reyes-Mendy, F., Arriagada, R. & Castillo, B. Assessing the implementation of marine ecosystem based management into national policies: Insights from agenda setting and policy responses. Mar. Policy 92, 40–47 (2018).
68. Johnson, D. S. Category, narrative, and value in the governance of small-scale fisheries. Mar. Policy 30, 747–756 (2006).
69. Cole, S. M. et al. Gender accommodative versus transformative approaches: a comparative assessment within a post-harvest fish loss reduction intervention. Gend. Technol. Dev. 24, 48–65 (2020).
70. Coté, C. "Indigenizing" Food Sovereignty. Revitalizing Indigenous Food Practices and Ecological Knowledges in Canada and the United States. Humanit. Rep. 5, 57 (2016).
71. H V Kuhnlein, A. & Receveur, O. Dietary Change and Traditional Food Systems of Indigenous Peoples. (2003) doi:10.1146/annurev.nu.16.070196.002221.
72. Hawley, N. L. & McGarvey, S. T. Obesity and diabetes in Pacific Islanders: the current burden and the need for urgent action. Curr. Diab. Rep. 15, 29 (2015).

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

ENDING HUNGER BY 2030 – POLICY ACTIONS AND COSTS

by Joachim von Braun, Bezawit Beyene Chichaibelu, Maximo Torero Cullen, David Laborde and Carin Smaller

I. INTRODUCTION - THE NEW RESEARCH BASIS

As the most widely-recognized definition of bioeconomy, the 2030 Agenda for Sustainable Development pledged to move away from growing inequality to more inclusive, shared growth, away from ecocide, mass extinction of our plant and animal biodiversity, and waste and destruction of our planet's abundant but still finite natural resources to practices that respect and protect our common home, and away from activities that expose hundreds of millions of people to the insidious effects of rising global temperatures and its consequences for climate risks. At the heart of the 2030 Agenda was a promise to prioritize to eradicate poverty and end hunger and malnutrition in all their forms.

Too many people in the world today do not have access to sufficient, affordable, safe and healthy foods. About three billion people in the world cannot afford a healthy diet.[1] To address this global challenge,

ABOUT THE AUTHORS

Joachim von Braun, Professor, Director at Center for Development Research (ZEF) Bonn University

Bezawit Beyene Chichaibelu, Senior Researcher at ZEF Bonn University

Maximo Torero Cullen, Chief Economist Food and Agriculture Organization (FAO)

David Laborde, Senior Research Fellow International Food Policy Research Institute (IFPRI)

Carin Smaller, Director Agriculture, Trade & Investment at International Institute for Sustainable Development (IISD)

G7 heads of states at their Summit in Elmau in 2015 committed to lifting 500 million people out of hunger and malnutrition by 2030, i.e. 72 percent of the total undernourished in 2019 and 60 percent of the total including COVID-19 projections in 2020,[2] as part of a broader effort to be undertaken with partner countries to support the 2030 Agenda for Sustainable Development, i.e. Sustainable Development Goal (SDG) 2 to end hunger and malnutrition by 2030 (Box 1).

Obviously, more and different investments and policy actions are needed to reach a world without hunger and malnutrition. We conceptualize ending hunger from different angles: as an important and feasible investment opportunity from a human rights perspective, as a humanitarian obligation, and for economic development. Experiences with COVID-19 and related responses from societies and political leadership tell us that significant action is possible. The hunger problem can be solved and deserves such action. The UN Secretary General's Food Systems Summit, and reform and policy efforts in support of the SDGs in many regions and countries, including by the EU and Germany, offer opportunities to take related interventions forward.

This policy brief is a call to action from the research community to not only address the problems of hunger, malnutrition and poverty, but to actually act and invest and adapt policies to reach SDG 2 by 2030.

BOX 1: SUSTAINABLE DEVELOPMENT GOAL NO. 2

END HUNGER, ACHIEVE FOOD SECURITY AND IMPROVED NUTRITION AND PROMOTE SUSTAINABLE AGRICULTURE

2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round

2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under five years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons

2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment

2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality

2.5 By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed

2.a Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks to enhance agricultural productive capacity in developing countries, in particular least developed countries

2.b Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round

2.c Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility

From the 2030 Agenda for Sustainable Development: https://sdgs.un.org/2030agenda

1 FAO: The State of Food Security and Nutrition in the World 2020: Transforming food systems for affordable healthy diets, 2020.

2 Estimates as reported in FAO: The State of Food Security and Nutrition in the World 2020, and consistent with Laborde and Smaller (2020), What Would it Cost to Avert the COVID-19 Hunger Crisis?, Ceres2030.

The findings presented here are based on a set of comprehensive and long-term research programs and partnerships among a large international research community[3] to identify high-impact, cost-effective interventions that can address the challenges of SDG 2 and the related targets. This policy brief builds on findings from two costing exercises: the marginal abatement cost curves (MACC) approach, and the computable general equilibrium (CGE) modeling approach. The purpose of the use of different research approaches and methodologies is to identify levels of coherence and consistencies of results that may lend credibility to proposed policy actions and investments. Conceptually, the two approaches have complementarities as both envision sustainable development, and both aim at one or more SDG 2 core targets (Box 1). Moreover, differences of findings between a modeling approach (which is constrained in this research by environmental targets and the doubling of incomes of small-scale producers), and using a marginal abatement cost curve approach (without capturing synergies or trade-offs) are presented. As shown below, both approaches show results that are consistent.

II. THE STATE OF HUNGER AND DETERMINANTS OF PROGRESS

Recent global projections have shown that the world is not on track to achieve Zero Hunger and Malnutrition by 2030 in line with SDG 2. In the past few years, the number of undernourished people has been on the rise again, from 653 million people in 2015 to 690 million people in 2019.[4] The majority of the world's undernourished – 381 million – are found in Asia while Africa – currently home to 250 million undernourished people – is the region with the fastest growth. Considering the total number of people affected by moderate or severe levels of food insecurity, an estimated 2 billion people in the world did not have regular access to safe, nutritious and sufficient food in 2019 and 3 billion people could not afford healthy diets.[5]

Without a more resolute response, the number of people suffering from hunger will surpass 840 million by 2030, or 10 percent of the global population. The world is also not on track to achieve the 2030 targets for child stunting and low birthweight, important indicators of severe malnutrition. According to estimates, in 2019 21.3 percent (144 million) of children under five years of age were stunted, 6.9 percent (47 million) were wasted and 5.6 percent (38.3 million) were overweight. Foresight studies agree that without a determined effort to fight climate change and mitigate its negative consequences, the adverse effects as well as widening gaps of inequality will make it difficult to achieve the goal of ending hunger and malnutrition by 2030.

COVID-19 is expected to worsen the overall prospects for food security and nutrition as food insecurity may appear in countries and population groups that were not previously affected. A preliminary assessment suggests that the pandemic may add up to 132 million people to the total number of undernourished in the world in 2020.[6] Beyond its short-term macroeconomic impact, the Covid-19 crisis could undermine the long-term well-being of vulnerable populations and eco-nomic productivity by depriving them from access to essential health, education and nutrition services.

III. COSTS AND TARGETING POLICIES AND INVESTMENTS TO MEET THE G7 ELMAU COMMITMENTS AND ENDING OF HUNGER

Investments needed to end hunger and all forms of malnutrition are likely to be extensive, costly and difficult to implement, but also promise high returns in terms of lives saved, people's well-being and productivity. Identifying optimal and least-cost investment options is important for practical policy-making. Using the **MACC** approach, 22 different interventions were assessed to identify least-cost investment options with the highest potential for reducing hunger and malnutrition.[7] The information about the interventions was drawn from best available evidence-based literature, including modeling studies and impact assessments. Some of these interventions can be implemented in

3 International Food Policy Research Institute (IFPRI), International Institute for Sustainable Development (IISD), and Cornell University: Ceres2030: Sustainable Solutions to End Hunger; Ending Hunger, Increasing Incomes, and Protecting the Climate: What would it cost? 2020.
Center for Development Research (ZEF), University of Bonn and United Nations Food and Agriculture Organization (FAO): Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct. 2020.
ZEF and Akademiya2063. 2020. From Potentials to Reality- Transforming Africa's Food Production, Bonn and Dakar. Oct. 2020.

4 FAO: The State of Food Security and Nutrition in the World 2020: Transforming food systems for affordable healthy diets, 2020.

5 FAO: The State of Food Security and Nutrition in the World 2020: Transforming food systems for affordable healthy diets, 2020.

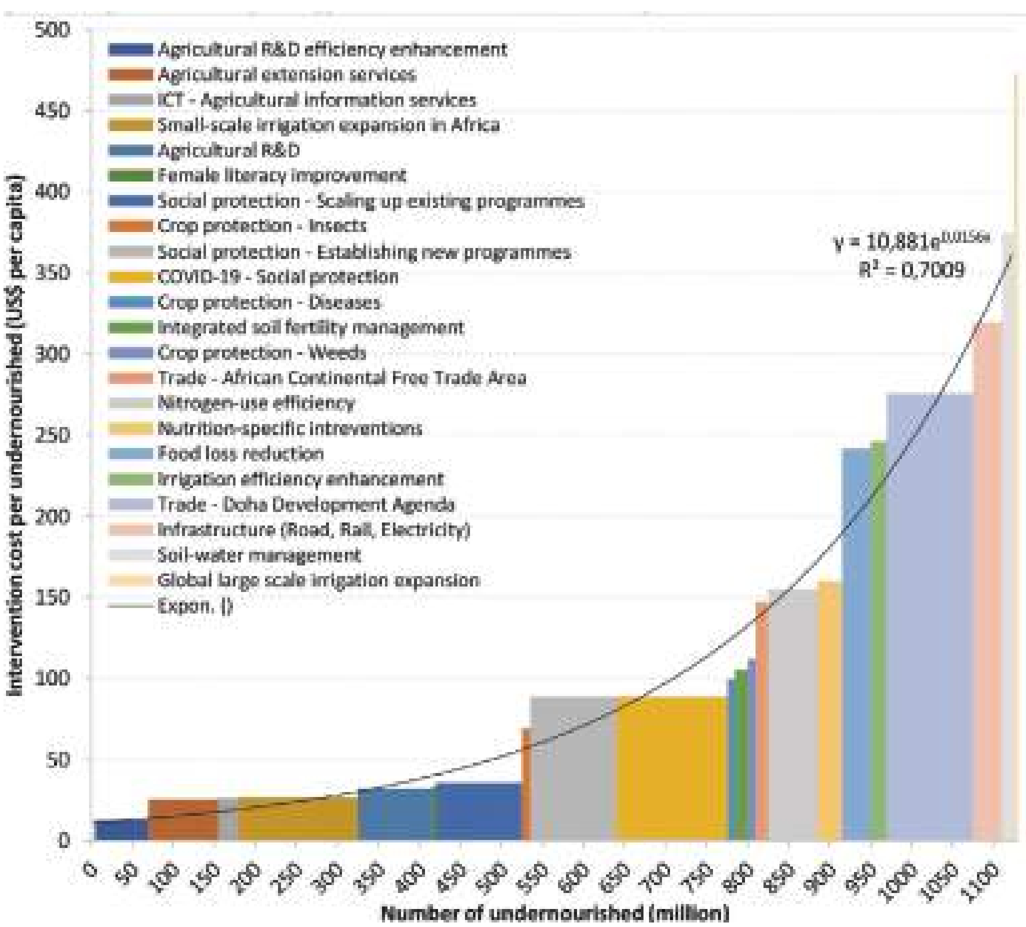
6 FAO: COVID-19 global economic recession: Avoiding hunger must be at the centre of the economic stimulus, 2020.

7 ZEF and FAO (2020) Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct. 2020.

the short-term (such as social protection), others in the longer-term (such as agricultural R&D, or soil fertility management). This assessment can broadly guide global and country efforts to achieve the SDG 2 targets by 2030. The results from the MACC indicate that

1. Achieving SDG 2 does not have to be prohibitively expensive, provided that **a mix of least-cost measures with large hunger and malnutrition reduction potential** are prioritized. This requires not only immediate action, but also an optimal phasing of investments by frontloading investments with high longer-term impacts to reap their benefits before 2030.
2. A rapid response is needed to **reach the hungry soon** with social protection and nutrition programs, including those adversely affected by COVID-19 with job losses and other socio-economic consequences. Scaling up existing programs is possible at low costs per unit with large effects. An important action in Africa would be regional trade integration with the African Continental Free Trade Area (AfCTA).
3. In order to meet the aforementioned **G7 commitment of lifting 500 million people out of hunger and malnutrition** by 2030, G7 governments would need to increase their investments by about **US$ 11-14 billion** per annum over the coming ten years, namely in addition to what they and governments of low- and middle-income countries are already investing. This is roughly equivalent to a doubling of current G7 development assistance for agriculture, food security and rural development. The mix of the identified low-cost, high-impact interventions include agricultural R&D, agricultural extension services, digital agricultural information systems, small-scale irrigation expansion in Africa, female literacy, and some scaling up of existing social protection programs (Figure 1).[8] Clearly, this portfolio is hunger-reducing in

Figure 1 Marginal cost curve of the suggested interventions to eradicate hunger and malnutrition



Note: The MACC for hunger shows the cost of each hunger reduction measure such that each bar represents a single intervention where the width shows the number of individuals lifted out of hunger, the height its associated per-capita cost, and the area its associated total cost. The total width of the MACC reflects the total hunger reduction possible from all interventions, while the sum of the areas of all of the bars represents the total cost of reducing hunger (PoU) through the implementation of all interventions considered. The positions of the bars along the MACC reflect the order of each intervention by their cost-effectiveness. When moving along the MACC from left to right, the cost-effectiveness of the interventions declines as each next intervention becomes more expensive than the preceding.

Source: ZEF and FAO (2020) Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct 2020

8 ZEF and FAO (2020) Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct 2020
9 When mentioning “ending hunger”, it is assumed that there is about a 3 percent transitory prevalence of undernutrition (PoU) not identified by PoU measurement.

sustainable ways as most of the interventions are also income-enhancing and empowering, not just short-term hunger-reducing.

4. **Ending hunger**[9] under a scenario of adverse trends would obviously require larger additional investments. We assess the costs of such a scenario that factors in both a continuation of the limited progress in hunger reduction as observed in the past five years as well as the additional threats posed by the COVID-19 pandemic which together could lead under business-as-usual to hunger of about 840 to 909 million people in 2030. To prevent this outcome it obviously would require significantly higher investments than to lift 500 million out of hunger, resulting in the need of government investments of about **US$ 39 to 50 billion** per annum over the ten years until 2030, that is in addition to what governments are currently already investing. In this case, both donor and developing countries would have to bear a fair share of the financial burden. The promising investments and policy actions mix includes expanded new social protection programs, crop protection, integrated soil fertility management, the AfCTA, fertilizer-use efficiency, and child nutrition programs.[10]

It is important to note that the MACC consider each intervention independently with its marginal costs and hunger reduction effects. As a result, beneficial synergies among interventions are not captured. This implies that costs are probably overestimated and hunger reduction impacts underestimated although there could also be trade-offs between interventions. This is one reason why these estimates are compared with comprehensive modeling that may capture synergies and trade-offs.

The investments prioritized here contribute not only to reductions in hunger and malnutrition, but also to long-term development and sustainability, including beyond 2030. The mix of investments strengthens the resilience of populations affected by hunger today or are at risk of hunger in this decade. Investments in female literacy and nutrition-specific interventions would reduce **child malnutrition** (stunting among children below the age of five years) by about 34 million at a total incremental average cost of about US$ 5 billion per year. Additionally, taking all of the other hunger reduction measures mentioned in Figure 1 together, the number of stunted children could be reduced by about 40 million without additional incremental cost.[11]

The MACC focused on the impacts of interventions on SDG 2 indicators related to hunger and malnutrition (2.1 and 2.2). In addition, SDG 2 recognizes the importance of significantly **raising the productivity and incomes of small-scale food producers** as an integral part of hunger reduction strategies (2.3). Most of the investments considered for ending hunger also support the income and productivity targets. A recent analysis of different strategies to increase the supply of food from small-scale production systems for affordable, safe and healthy diets from sustainable use of resources in **Africa** suggests a set of key actions[12], including:

1. Investments in **young women and men**, i.e. vocational training and extension services, to improve skills for all core and support professions along the entire value chain.
2. Investments in **innovation and related agricultural research** on crops, animal production, agro-forestry and fisheries, and support of producer- and local private sector-led development and adoption of environmentally sustainable small-scale irrigation, rural energy, digitalization and mechanization of farm operations.
3. Investments in **mobile connectivity** of rural areas and across Africa as a perquisite for digital tools to be widely and effectively used in the food and agriculture sector.
4. Improvements in **trade and market access** through rural infrastructure investments, and facilitating the participation of small-scale producers and small businesses in inclusive local and continental value chains as well as the opportunities of the AfCTA.
5. Aligning development **support to Africa's own agricultural transformation agenda**, at the continental level, i.e. the African Union Agenda 2063 with the Malabo Declaration, and at the country levels, and sustaining and expanding development assistance in the aforementioned priority areas for agriculture development and food security.

10 Measures are also needed to overcome hunger related to complex emergencies combined with violent conflicts and wars. These were not included in the calculations presented here.

11 ZEF and FAO (2020) Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct 2020

12 ZEF and Akademiya2063 (2020). From Potentials to Reality: Transforming Africa's Food Production. Bonn and Dakar, Oct. 2020. (The study was carried out for the African context, but the findings are transferable to other countries with comparable small producer-dominated production systems.)

IV. USING A COMPUTABLE GENERAL EQUILIBRIUM MODEL TO ESTIMATE THE COST OF ENDING HUNGER, DOUBLING AVERAGE INCOMES OF SMALL-SCALE PRODUCERS AND PROTECTING THE CLIMATE

In Ceres2030: Sustainable Solutions to End Hunger researchers sought to answer two linked questions: First, what does the published evidence tell us about agricultural interventions that work, in particular to double the incomes of small-scale producers and improve environmental outcomes for agriculture? And second, what will it cost governments to end hunger, double the incomes of small-scale producers and protect the climate by 2030? The project focuses on three of the five targets in SDG 2 and looks at the public spending needed in low- and middle-income countries, including the contribution from donors through official development assistance (ODA). This brief focuses on the answer to the second question. The answer to the first question is published as a special collection in Nature Research.[13]

Ceres2030 used a computable general equilibrium (CGE) model to estimate the additional donor spending that is needed over the period 2020-2030 by allocating financial resources to a portfolio of public policy interventions (such as social protection programs, rural infrastructure or payments for ecosystem services). The model also includes data from the international level all the way down to the household level, allowing for simulation of targeted public investment across countries and population groups. However, it does not assume perfect targeting (e.g. a food subsidy program will be allocated based on income status, not hunger status, since the latter is not observable by policy makers). In order to simulate the portfolio of interventions, the model uses fourteen policy instruments, grouped into three categories: (1) enabling inclusion, (2) on the farm, and (3) food on the move (see Box 3. for details).

Each instrument has a cost (public and/or private), and a marginal impact of structural variables (capital endowment, labor productivity) that will contribute to the final outcome (e.g. caloric available per household) after being mediated by the economic system.

For example, the research and development spending in the Consultative Group on International Agricultural Research (CGIAR) system contributes to increasing agricultural productivity by paying a fixed cost in research services, but also provides larger benefits for a large number of low- and middle-income countries over time, while a fertilizer subsidy will reduce the fertilizer cost paid by the farmers receiving it on a recurrent basis. 14 policy instruments were modeled, based on existing data sources and a number of new parameters from the collection of evidence syntheses published in Nature Research. This list is aimed at capturing interventions for which data and parameters are available, especially regarding the actual cost (direct and opportunity costs) (See Box 2).

The results from the modeling indicate that:

1. Donors need to contribute an additional **US$ 14** billion per year on average until 2030 to largely end hunger of more than 490 million people, double the incomes of small-scale producers, and protect the climate. Donors currently spend US$ 12 billion per year on agriculture, food security and nutrition and therefore need to double their contributions to meet the goals.[14] However, ODA alone will not be sufficient. Additional investments of **US$ 19 billion** per year on average will have to be made by low- and middle-income countries.
2. The additional spending will not only lift 420 million people out of hunger but also double the average incomes of 545 million producers and their families, and limit greenhouse gas emissions for agriculture to the commitments made in the Paris Agreement.[15]
3. Any delay in spending will not only have human costs but will also increase the total costs. Early spending, on the other hand, allows investment in interventions that take more time – like R&D – but have a bigger pay-off.

13 Sustainable Solutions to End Hunger, Nature Research, 2020.

14 All figures of existing donor spending represent 5-year averages calculated using data for 2014-2018 extracted from the OECD Development Assistance Committee (DAC) Creditor Reporting System (CRS) database (OECD, n.d.(a)). Spending on food security and nutrition is defined by the DAC codes: basic nutrition (12240), agriculture (311), agro-industries (32161), rural development (43040) and food aid (52010). All values refer to total disbursements from all donors of ODA and are stated in constant 2018 US dollars.

15 The targets are defined by SDGs 2.1, 2.3 and 2.4, under some constraints (mainly from SDG 2.4, which commits to minimizing the use of land, energy and fertilizer for agriculture through a reduction in greenhouse gas emissions). For target 2.1, the baseline simulates how hunger, as measured by the FAO's prevalence of undernutrition (PoU), would increase in the business-as-usual world. For target 2.3, the productivity and incomes (interpreted in the model as net incomes) of small-scale producers double on average in the scenario as compared with the baseline. For target 2.4, greenhouse gas emissions for agriculture conform to the commitments made in the NDCs from the UNFCCC Paris Agreement in 2016. The NDCs are both integrated into the baseline and a target in the model.

BOX 2: Interventions and Policy instruments considered in the Ceres2030 framework

Intervention	Policy Instrument
ENABLING INCLUSION	
Social protection	Food subsidy
Education	Vocational training
ON THE FARM	
Input subsidy	Fertilizer subsidy
Production subsidy	Investment subsidy
	Capital endowment
	Production subsidy
R&D	National Agricultural Systems (NARS)
	CGIAR
Extension services	Extension services
Rural infrastructure	Irrigation
Livestock subsidy	Agroforestry
	Improved forage
FOOD ON THE MOVE	
Post-harvest losses	Storage
Rural infrastructure	Roads

This list of interventions is not exhaustive. Other policies are essential to improve the enabling environment (e.g. land reforms), while critical dimensions, such as gender equality and women's empowerment, should be embedded in each intervention and not seen as a separate tool.

4. A portfolio of interventions is needed to achieve the multiple SDG 2 targets. The interventions in the model are balanced according to the impact on greenhouse gas emissions, economic growth, and the country context. The modeling offers a starting point for considering proper portfolio balance among the three categories of interventions: (1) enabling inclusion, (2) on the farm, and (3) food on the move.

The model's key strength is that it captures synergies and trade-offs among interventions, along with a multitude of other complex interactions in the economy. This allows it to optimize public investment in its simulation of the achievement of SDGs 2.1, 2.3 and 2.4, minimizing public costs. In optimizing the public investment, the model intrinsically specifies how the public spending is distributed among the interventions, how much is spent each year from 2020 to 2030, and how much is spent per country. This capturing of complex interactions highlights the need for a mix of interventions, integrated together in the proper proportions.

The model is not, of course, omniscient. It can only model economic relationships for which there is widely available and consistent data. It also makes the underlying assumption that interventions are used efficiently at the microeconomic level (e.g. proper location of new roads, selection of the best technical solution in a given context). Therefore, it could not be properly interpreted and used independently of the growing literature on how successful interventions should be implemented.

V. SCALING NATIONAL AND INTERNATIONAL DEVELOPMENT ACTIONS

Some low- and middle-income countries have made significant progress towards reaching SDG 2 in the last decade. These best-performing countries achieved on average more than a 50 percent reduction in hunger.[16] Important lessons can be drawn from the factors that drove this performance. The agriculture sector continues to play an important role in these economies in terms of its contribution to GDP employment. The countries spent substantially more on agriculture and

16 ZEF and FAO (2020) Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct 2020.

experienced relatively high agricultural growth. However, what they all have in common is that manufacturing is gaining in importance and labor is gradually moving out of agriculture and rural areas. They also showed higher growth rates in capital formation and GDP compared to worse performing countries. These findings emphasize that hunger reduction goes hand in hand with improvements in various human and macroeconomic development outcomes, such as poverty reduction and fiscal attention to agriculture.

ODA also has an important role to play towards ending hunger and malnutrition. At Elmau, the G7 countries committed to increasing bilateral and multilateral assistance to achieve SDG 2. Analyses of ODA flows[17] that relate to this commitment show that ODA from G7 countries specifically allocated to food security and rural development slightly more than doubled between 2000 and 2018 to reach US$ 17 billion. Most of this ODA was targeted at countries with a relatively higher prevalence of undernourishment, notably in Sub-Saharan Africa, as indicated by these data: ODA represented 36 percent of the foreign finance received by African countries south of the Sahara, compared with 31 percent from overseas person al remittances and 23 percent from foreign direct investment.[18] In other regions, ODA is less dominant with remittances representing 55 percent of foreign finance in South Asia.

In 2018, a significant portion of G7 member countries' ODA was allocated to agricultural development, and water and sanitation, food aid and environmental protection also receiving substantial investments. Germany has increased contributions to these sectors the most in recent years, followed by Japan and France. Analyses show that between 2000 and 2018, agricultural ODA helped to reduce hunger and child malnutrition, highlighting the importance of agricultural ODA to achieve improvements in hunger and malnutrition rates in the coming decade.

VI. CONCLUDING STATEMENT: END HUNGER CAN BE DONE

In the past few years undernutrition has increased, but ending hunger and malnutrition by 2030 is still within reach. The research presented here is in agreement that an optimal portfolio of investments by the development partners supporting countries' own initiatives is feasible to reach the SDG 2. Many emerging economies have successfully cut hunger drastically in the past two decades through policy reform, investments and actions, in particular by accelerating investments in agriculture and thereby overcoming the undercapitalization of small-scale production.

The research agrees that between now and 2030 G7 governments need to double their efforts to achieve the Elmau commitment. That means an additional US$ 14 billion per year is needed on top of current spending, which stands at about US$ 12 billion per year. This effort, combined with more resolute efforts from developing countries would also mean a significant step forward towards achieving SDG 2 in its entirety.

It will also require a focus of the additional resources towards Africa where the highest levels of hunger and dependency on external resources will be found in this decade. Delaying these essential investments further will make achieving SDG 2 more difficult and more expensive, while acting sooner can improve lives and our environmental future.

In sum:

1. Sound investment will facilitate a world without hunger. This includes, to expand and intensify nature-positive agricultural production that is resilient to climate threats, and build back better from the COVID-19 pandemic.
2. Donors and affected partner countries must double their investments from now until 2030, and for OECD donors this means a total of about USD 14 billion more per annum.
3. In countries with hunger problems, agriculture must be a focus, whereby donors and partner countries should agree on and implement efficient packages of investment and policy measures.
4. Bring forward investments in social security to address acute hunger, and in research and training, because that takes time to take effect.

This Brief was prepared by members of the Scientific Group and members of its Research Partners.

17 ZEF and FAO (2020) Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2), Bonn and Rome, Oct 2020.
18 Mali Eber-Rose, Sophia Murphy, David Laborde. Ending Hunger Sustainably: Trends in ODA Spending for Agriculture, 2020. Ceres2030-IISD, Geneva.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
IFPRI

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

FINANCING SDG2 AND ENDING HUNGER

by Eugenio Díaz-Bonilla

EXECUTIVE SUMMARY

Among the important tasks of the United Nations Food Systems Summit (UNFSS) is identifying ways to finance the transformation of the global food system. This report analyses options for financing a specific, but crucial, part of the overall food system transformation, namely achieving SDG2 (and in particular "zero hunger") by 2030, and it examines the role of external finance in this effort. It reviews costs and possible resources and offers ideas for the effective mobilisation and use of the funds.

FOOD SYSTEMS TRANSFORMATION AND SUSTAINABLE DEVELOPMENT GOALS

The operation of food systems affects incomes and employment, poverty and food security, diets, health, and nutrition, energy sources and uses, climate change, environmental sustainability, biodiversity, and ecosystems, and even aspects of peace and governance. Hence, the adequate functioning of food systems is crucial for achieving the Sustainable Development Goals (SDGs) by 2030. However, current food systems are falling short in many of these economic, social, environmental, and political dimensions, and there are mounting calls for their transformation. This will

ABOUT THE AUTHOR

Eugenio Díaz-Bonilla, Head of Latin American and Carribean Program at International Research Policy Institute (IFPRI)

The author acknowledges the detailed and very useful comments from Joachim von Braun, Johan Swinnen, and Rob Vos. Those comments significantly improved this document. However, they are not responsible for any of my remaining errors and omissions.

require defining the specific objectives desired and the interventions, costs, incentives, and financing that would lead to their achievement.

Financing food systems transformation will involve a variety of financial resources, including funds "internal" to food systems (consumer food expenditures and agrifood industry investments) and "external" funds (international development flows, public budgets, banking systems, and capital markets). The contributions of the different funding sources are likely to vary across different aspects of the transformation.

FINANCING OF SDG2 AND ENDING HUNGER

This paper focuses on one critical part of the overall food system transformation, namely achieving SDG2 (and in particular "zero hunger") by 2030. It explores the role of external finance in achieving SDG2, namely the availability and use of external flows to food systems that can augment the internal flows to help meet the additional costs of reaching SDG2 and ending hunger.

The paper reviews cost estimates from several studies and compares these with potential sources of funding. There are significant data limitations for this exercise. With the available data, estimates suggest that, in aggregate, sufficient additional resources are potentially available to finance the costs of ending hunger by 2030 (with "ending hunger" understood as lifting from 870 million to 1 billion people from hunger), including interventions that also contribute to nutritional objectives and mitigation and adaptation to climate change in agriculture.

However, to move from "potentially available" to actual mobilisation and effective use of those financial resources, several problems and constraints must be addressed, both at the aggregate level and at the country level. At the aggregate level, the expansion and adjustment of existing sources of funding are required. At the national (implementation) level, even when necessary financial resources can be effectively mobilised, they will only be utilised in effective programmes to end hunger and achieve SDG2 if individual countries are willing and capable of doing so. Therefore, institutional mechanisms are needed to support developing countries in the design, financing, and implementation of national programmes, particularly considering the fiscal constraints that have been created by government responses to the current pandemic.

Mobilising sufficient resources would require a series of changes for different sources of funds. Some ideas for mobilising these resources are listed below.

MOBILISING ADDITIONAL FINANCIAL RESOURCES

For public budgets

- Implement public expenditure and tax reviews to increase and reallocate agricultural subsidies in developing countries (about 50 billion dollars, without China) and scale up, better target, and redesign social safety nets using new and evolving cash transfer instruments that combine poverty, productive, nutritional, environmental, and financial inclusion components (such as the Cash Transfers Plus analysed by FAO or the evolving instruments of social inclusion considered by the World Bank).
- Increase public expenditures/investments in agriculture (for example, to an Agricultural Orientation Index [AOI] of 0.5) and social protection expenditures (to 2% of GDP).
- Strengthen revenues in developing countries through better tax administration and revision of sales, income, wealth, and trade taxes, and by implementing international initiatives to control corruption, tax evasion, and other practices that erode those countries' tax bases. The use of carbon taxes needs to be considered.

For banking systems

- Reactivate the tools of the "developmental central banks," using rediscounts to offer credit to small farmers, rural populations, and small and medium enterprises (SMEs) in food value chains (within a consistent monetary programme that controls inflation).
- Revitalise and modernise public development and agricultural banks (with incentives, performance metrics, and controls to avoid the problems of the past in this type of institution) to increase credit (supported by central bank discounts) and offer other financial services to small farmers, rural populations, and SMEs in food systems, with particular consideration for women, vulnerable ethnic minorities, and youth.
- Increase the AOI of agricultural credit to at least 0.5.

For capital markets

- Create a project preparation/incubation/acceleration facility to structure productive opportunities for small farmers into investable opportunities for impact investors, using economic, social, and environmentally sound technologies with the support of One CGIAR and national agricultural research institutes (NARIs). This facility can also support enhanced environmental lending by the agricultural public banks mentioned above.
- Design, guarantee, and launch a "zero hunger bond" (see below).

ZERO HUNGER BOND AND A ZERO HUNGER ALLIANCE & FUND

To finance food systems transformation to end hunger and achieve SDG2, the international development funds dedicated to agricultural and rural development, food and nutrition security, and environmental aspects of food systems would need to be increased by about 15 billion dollars annually, which implies doubling current levels. Two billion dollars of these 15 billion would be used to finance a Zero Hunger Alliance & Fund (ZHAF), designed to support institutionally and financially those countries that want to join a global partnership to end hunger.

Creation of the ZHAF would be complemented by the development of a "zero hunger bond," with 2% of the future issue of Special Drawing Rights (SDRs) of 650 billion dollars allocated to offer guarantees for this new bond. The zero hunger bond would help finance the economic, social, and environmental interventions (possibly a subcategory of "zero hunger green bonds") needed to achieve SDG2 and end hunger. These instruments can be perpetual or very long-termed bonds, with an adjustable coupon and a cap on the maximum interest rate.

This proposal follows the suggestions of global leaders (including Pope Francis) and builds on the idea of a Zero Hunger Fund presented by Action Track One of the UNFSS. The ideas developed here aim to guide the institutional design with experiences and lessons learned from other initiatives, including the Global Agriculture and Food Security Program (GAFSP), the Poverty Reduction Strategy Papers or Programmes (PRSPs), and GAVI, the Vaccine Alliance.

Key lessons from these experiences are: (1) the importance of supporting country-owned, medium-term, integrated programmes; (2) the need for clear and measurable objectives; (3) the strategic potential of scarce development funds to mobilise a much larger amount of financial resources, rather than financing individual, isolated projects directly; and (4) the benefits of flexible public-private institutions with strong coordination and operational capabilities.

Based on these lessons, the proposed ZHAF would have the following characteristics and objectives:

- It focuses on a clearly measurable objective: eliminating hunger by 2030.
- It is an independent public-private institution with a dedicated fund, and with personnel seconded from international organisations focusing on poverty, food security, and nutrition issues, who will work in close cooperation with local teams of partners in the participating countries, and as such form an Alliance.
- There will be a dedicated fund to: (a) cover the operational costs (but not the salaries of the seconded personnel); (b) hire technical and operational expertise needed to support the countries in defining their programmes and mobilising the human, financial, and institutional resources to carry them out; (c) de-risk some financial operations to mobilise private capital (such as the issuance of zero hunger bonds); and (d) eventually, finance some interventions directly. The largest share by value of those funds will be used for (c), but the most important use, operationally, will be for (b).
- Funding will come from the additional international development funds (as discussed above, about 2 billion dollars), plus an effort to mobilise private funds, with the target of obtaining commitments from at least 50 companies (from food and other sectors) to donate about 10 million dollars each (these companies will be recognised as Champions of the Zero Hunger Alliance). Combined, those funds would reach 2.5 billion dollars per year.
- In addition, 2% of the planned allocation of SDRs (or 13 billion dollars) will be used to design, launch, and guarantee zero hunger bonds (and zero hunger green bonds) issued by countries with "zero hunger programs" supported by the Alliance. Depending on how the guarantees are structured and maintained over time, they could multiply the value of the SDRs directly allocated to this initiative by a factor of more than 10.
- Most of these funds will be leveraged to mobilise the country-level sources of financing discussed above, through public budgets, banking systems, and capital markets.
- The Alliance will support financially and operationally those individual countries that sign agreements to join this global partnership to end hunger by 2030, helping them to identify the target population, define specific institutional, programmatic, and instrumental components, mobilise the necessary funding, and structure the partnerships needed to carry out the programmes to end hunger by 2030.
- In particular, it is suggested to expand the use of the new instruments that combine cash transfers based on poverty with additional productive, nutritional, environmental, and financial inclusion components.

The institutional arrangement outlined here has several advantages, including that: It supports the country members of the Alliance in implementing country-owned, country-coordinated, integrated programmes. It focuses on a single and measurable objective (ending hunger by 2030) but, given the type of agricultural technologies and environmental interventions supported, it also contributes to crucial objectives related to climate change mitigation and adaptation. It mobilises a significantly larger volume of funds than those directly allocated to the Alliance. By relying on temporary secondment of personnel from existing organisations, it reduces the risk of creating another permanent international bureaucracy. Finally, it has a flexible public-private institutional structure.

A. INTRODUCTION

The operation of food systems affects incomes and employment, poverty and food security, diets, health, and nutrition, energy sources and uses, climate change, environmental sustainability, biodiversity, and ecosystems, and even aspects of peace and governance. Hence, adequate functioning of those food systems is crucial for achieving the SDGs by 2030 (von Braun, Afsana et al. 2020). However, current food systems are falling short in many of these economic, social, environmental, and political dimensions, and there are mounting calls for their transformation. This will require defining the specific objectives desired and the interventions,[1] costs, incentives, and financing that would lead to their achievement.

This paper focuses on the transformation of food systems to help achieve crucial components of SDG2[2] and, in particular, ending hunger by 2030. This narrows the analysis of food systems to several relevant aspects, notably (1) agricultural production and rural development within the more general operations of food value chains, and (2) poor and hungry consumers, rural and urban, as part of the more general problems of diets and health that affect a larger number of consumers.[3] Even with a focus on SDG2, the targets and interventions considered have important implications for a variety of nutritional and environmental objectives.

The paper compares the additional costs of achieving SDG2, including zero hunger (as estimated by von Braun, Chichaibelu et al. [2020] and studies referenced there), with potential sources of funding. The estimates of potential funding use the framework in Díaz-Bonilla, Swinnen, and Vos (2021), which identifies two flows of funds "internal" to food systems (consumer food expenditures, on the one hand, which comprise the sales/revenues of the agents in the agrifood system, on the other), and four that are "external" to food systems (international development flows, public budgets, banking systems, and capital markets). The main question analysed here is, given the estimated costs involved in such a transformation, what are the options to finance the interventions needed, what is their quantitative availability, and how can those potential sources of finance be mobilised and used effectively to achieve SDG2 and end hunger.

Adequate macroeconomic policies,[4] a supportive business environment, and peace are basic requisites for the operation of food systems. Furthermore, different policy interventions can influence the size and allocation of consumer expenditures and the productive outlays of the operators of food value chains (the internal flows) in ways that support the achievement of different SDGs (see a discussion in Díaz-Bonilla, Swinnen, and Vos 2021). However, those reallocations within the internal flows are not the focus of this paper. Rather, it analyses the availability and utilisation of external flows to food systems, which can augment the internal flows (operating under an adequate set of incentives defined by more general macroeconomic policies) to finance the additional costs of reaching SDG2 and ending hunger.

This paper is structured as follows. Section B focuses on the costs of achieving SDG2, based on the work referenced in von Braun, Chichaibelu et al. (2020). Then those policy interventions and costs are analysed against a matrix of potential sources of financing, using the framework in Díaz-Bonilla, Swinnen, and Vos (2021). Section C presents estimates of the current

1 "Interventions" refers generally to public sector actions, including policies, programs, investments, expenditures, taxes and subsidies, laws and regulations, and institutional aspects, that seek to address a specific problem.

2 The focus is on 2.1 "end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round"; 2.3 "double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers…"; and 2.4 "ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production…" In the text, references to SDG2 must be understood in this vein.

3 A more general discussion about foods systems, financing, and SDGs can be found in the framing note (Food-Systems-Summit-Finance-Lever-framing-note-2021.pdf) and at https://foodsystems.community/communities/lever-of-change-finance/documents/; and in Díaz-Bonilla, Swinnen, and Vos (2021).

4 See Díaz-Bonilla (2015) for a discussion of macroeconomic policies in relation to agriculture and food security.

values of the external funds that can complement the internal flows[5] and help finance the additional expenditures and investments needed to achieve SDG2 and end hunger. Section D compares the costs in section B with the availability of funds estimated in section C, and evaluates different financial alternatives, suggesting some specific adjustments to effectively mobilise the additional resources needed. Section E argues that it is not only a matter of financing a set of interventions but also of designing and implementing them adequately, which depends, to a large extent, on the willingness and capabilities of individual countries. Therefore, section F discusses a separate proposal, called a ZHAF (based on the idea of a fund to end hunger, advanced by different global leaders,[6] and presented as a specific proposal by Action Track One). Section G summarises all proposals and section H concludes.

B. COSTS OF INTERVENTIONS TO ACHIEVE SDG2 AND END HUNGER

The analysis of the costs related to SDG2 and ending hunger follows the work reported in von Braun, Chichaibelu et al. (2020), with the background of two other studies, ZEF and FAO (2020) and IFPRI, IISD, and Cornell University (Laborde, Parent, and Smaller 2020). The latter (part of the project called Ceres2030: Sustainable Solutions to End Hunger[7]) considers fourteen interventions and policy instruments to end hunger, increase agricultural incomes, and achieve some environmental outcomes. ZEF and FAO (2020) calculates the additional costs of lifting people out of hunger and malnutrition using a variety of interventions, selected by their favourable impacts on the elimination of hunger. Those interventions also support other components of SDG2 and, in particular, given the technologies considered, they are aligned with the objectives of mitigation and adaptation to climate change. The number of people who may be lifted from hunger depends on the range of interventions considered. These estimates are shown in Table 1.

The costs of eliminating hunger are not linear, with each further reduction in the number of people affected becoming costlier (ZEF and FAO 2020). The largest estimate, of about 163 billion dollars annually,[8] would lift about 1,050 million people from hunger by 2030. While the projections under business-as-usual assumptions for the number of hungry people in 2030 are about 900 million (under intermediate scenarios of climate change; see ZEF and FAO 2020), this number does not consider the possibility of additional humanitarian, health, or environmental crises. In section C, for the matrix of financing, the focus is on the intermediate estimate, namely lifting 870 million people from hunger, but the target of 1 billion lifted from hunger is also referenced, both as a cushion and because the additional interventions support further environmental objectives, particularly for climate change adaptation and mitigation.

Table 1 Estimates of Ending Hunger and other SDG2 Goals

Source	People lifted from hunger (million)	Additional cost per year (billion dollars)
IFPRI, IISD, Cornell (2020) (Ceres 2030)	490	33
ZEF and FAO (2020)	870	56
ZEF and FAO (2020)	1050	163

Sources: Based on the cited studies.

5 Internal flows of funds in food systems are estimated in a quantitative background paper at about 7,700–8,300 billion dollars, as an average of 2014–2018 in current dollars, corresponding to food expenditures by consumers, which are sales from the perspective of all the operators of the food value chains. Different policy interventions can influence the size and allocation of internal flows in ways that support the achievement of different SDGs (see a discussion in Díaz-Bonilla, Swinnen, and Vos 2021).

6 See, for instance, Pope Francis, who argued that "A courageous decision would be to establish a "Global Fund" with the money that is used for weapons and other military expenditures, in order to definitively eliminate hunger and contribute to the development of poorer countries. In this way, many wars and the migration of many of our brothers and sisters and their families, forced to abandon their homes and countries to seek a more dignified life, would be avoided…" http://www.vatican.va/content/francesco/en/messages/food/documents/papa-francesco_20201016_messaggio-giornata-alimentazione.html.

7 https://ceres2030.org/

8 Another recent analysis (FOLU 2019) estimates the costs of 10 "transitions" needed for the transformation of food systems at 300–350 billion dollars per year until 2030. Those transitions involve several SDGs; but considering only those more directly related to SDG2, the costs would be about 170–190 billion dollars, which is in the same range as the estimates in ZEF and FAO (2020).

C. POSSIBLES SOURCES OF FUNDING

Each of the next subsections discusses quantitative estimates[9] of the current values of the external sources.[10] They will be compared later with the additional financing needed (as discussed in the previous section), to give an idea of the extra financial effort required.

1) International development flows

International development flows include concessional development assistance and non-concessional lending[11] by bilateral agencies, multilateral development banks (MDBs), and some large private philanthropic funds. FAOSTAT provides data on development flows both as commitments and as gross disbursements.[12] Using disbursements[13] in current values, the annual average for the 2014-2018 period was about 256 billion dollars for all uses/sectors, and 11.1 billion for agriculture, forestry, and fishing (AFF),[14] or some 4.3% of all development flows.

ZEF and FAO (2020) also calculate development flows to other sectors related to SDG2 (such as water and sanitation), which produces a higher estimate of the disbursements going to food security and rural development in 2018 of about 15 billion dollars, and of commitments to about 17 billion dollars.

2) Public budget

The public sector implements many interventions that affect the operation of food systems. Here the focus is on public expenditures. Considering the interventions discussed in section B related to SDG2,[15] the analysis centres on two main types of public expenditures: on AFF and on social protection. A brief discussion of additional fiscal expenditures related to the COVID-19 pandemic is also included.

a) Agriculture, forestry, and fishing

Data from FAOSTAT are based on the IMF functional classification of expenditures.[16] Table 2 shows total government outlays (current US dollar average 2014-2018) and outlays on AFF, using FAO's regional classification of countries.[17] Public expenditures for AFF by developing countries[18] (not counting China) are about 86 billion dollars. If all outlays are considered, public expenditures by developing countries amount to almost 6,500 billion dollars (but only about 3,700 billion dollars if China is not included).

Table 2 shows the outlays related to AFF as a percentage of all public outlays. Developing countries spend a larger percentage of their budgets on agriculture-related activities than developed countries do. However, this percentage does not consider the size of the agricultural sector, which is taken into account in the AOI. The AOI is calculated as the share of agricultural expenditures in total expenditures divided by the share of agricultural GDP in total GDP. A number smaller (greater) than 1 indicates that the share of government spending on agriculture is less (more) than the share of agriculture in GDP, indicating that there would be under- (over-) spending in the sector relative to its economic relevance. The last column of Table 2 shows the median AIO values for the countries in each region. Clearly, developed countries spend more as proportion of their agricultural sectors than developing countries.

Of course, the levels of public spending alone do not determine agricultural performance, nor is there any

9 Details are in a background paper that is based on the structure of Díaz-Bonilla, Swinnen, and Vos (2021).

10 Remittances are an important flow of funds, estimated by the World Bank at about 700 billion dollars in 2019, of which about 550 billion were to developing countries. However, they are basically intrafamily flows, which may not be possible or desirable to reallocate through public policies.

11 That is, not having highly subsidized interest rates and very long terms for repayment of principal.

12 The Development Flows to Agriculture (DFA) dataset is based on OECD's Creditor Reporting System (CRS). It includes Official Development Assistance flows, Other Official Flows and Private Grants reported to the OECD.

13 The values of disbursements are different from the net flows in the case of loans (concessional or not) because repayments of the principal of the previous loans must be deducted. This is not the case for grants.

14 It includes Agriculture (which covers Agro-industry, General Environment Protection, Food and Nutrition Assistance, Rural Development), Forestry, Fisheries, and Other Agriculture, Forestry and Fishing.

15 The public sector also has outlays related to other components of the agrifood system that may impact several SDGs. They are not considered here because the focus of this paper is on SDG2. Also, those additional public outlays correspond to different agencies and sectors and collecting them requires a detailed, country-based, review of public expenditures.

16 Using the distinction made by FAO (2012), they cover public outlays in agriculture (aimed specifically at enhancing primary production) , but not for agriculture (which are government expenditures in other sectors that can also have a positive impact on the agricultural sector). Further, the classification does not include all the expenditures that can support the whole food system (see Díaz-Bonilla 2015).

17 Some countries report expenditure for the General Government, others only for the Central Government, and finally some of them report both. Table 2 has been calculated with the largest of the two values reported.

18 What is considered "developed" and "developing" countries varies across datasets. Therefore, the numbers presented must be considered approximations for those groups.

Table 2 Government Outlays (Current Billion Dollars, 2014–2018)

	Billions of current USD (average 2014–2018)			Coefficient
	Total Government Outlays	Outlays for Agriculture, Forestry, and Fisheries (AFF)	AFF as Share of Total (%)	AOI median
Africa	366.8	7.8	2.1	0.17
Asia developing	4587.5	324.9	7.1	0.35
(of which China)	2781.4	268.0	9.6	0.28
(of which India)	352.5	24.1	6.8	0.41
LAC	1531.6	21.2	1.4	0.38
Oceania	561.0	3.5	0.6	0.19
Northern America & Europe	16545.8	66.0	0.4	0.56
Developing	6485.9	353.8	5.5	0.30
Developing w/o China	3704.5	85.8	2.3	0.30
Developed	19269.3	121.1	0.6	0.42
Total	25755.2	474.8	1.8	0.37

Source: FAOSTAT.

formula to indicate whether a certain level of spending is more adequate than another. However, several studies show that the types of expenditure matter, particularly their orientation toward the provision of public goods, such as agricultural R&D (see for instance Fan, ed. 2008).[19] Furthermore, as noted, these numbers do not include public expenditures for agriculture, particularly in infrastructure, and, more generally, public outlays related to food systems as a whole. These considerations suggest the need to utilise a broader focus to analyse the level and composition of public expenditures at the country level (about 3,700 billion dollars of public expenditures in developing countries, not counting China) that are relevant for achieving the desired SDGs.

b) Social protection

Another important group of expenditures related to SDG2 and ending hunger are those for social protection, and within them, the programmes of social assistance (which refers to those more directly linked to poverty and vulnerability and that are financed by general revenues from the government and not by contributions from beneficiaries, known as "non-contributory programs"). Here the focus is on the social assistance programmes, using data from the World Bank's ASPIRE database.[20] Because these data are based on household surveys, they may not capture information about all programmes defined statutorily by governments. Moreover, the database focuses on developing and emerging countries only. However, it does provide a useful disaggregation of social protection programmes and of the distribution of benefits across populations.

Social assistance programmes included in the ASPIRE database are classified as conditional cash transfers, unconditional cash transfers, social pensions, school feeding, public works, food and in-kind programmes, health fee waivers, and other social assistance. Table 3 shows an estimate of the money allocated to those programmes (in current dollars for the period 2014-2018),

19 A separate quantitative background note also includes an analysis of the OECD data to evaluate the possibility of "repurposing 600 billion dollars in subsidies" as part of the financing of the transformation of food systems. They show that the amount of subsidies that can be repurposed (average 2014–2018 in current dollars) is less than 240 billion dollars (about 132.5 billion dollars in OECD countries, of which the EU represents 82.5 billion, and 105.8 billion dollars for non-OECD countries, of which China amounts to 62.1 billion dollars). For developing countries (not counting China but including OECD members that are developing countries), the value is about 52 billion dollars.

20 An estimate of expenditures on social protection in general is mentioned later.

with the first three programme types grouped together as Cash Transfers and Social Pensions (CT+SP).[21]

Total expenditures for social assistance by the countries considered are found to be somewhat less than 410 billion dollars annually (and about 260 billion dollars without China), with CT+SP as the main programme type in value terms.[22] Countries in the ASPIRE database spend on social assistance less than 1.2% of their GDP (median value for those countries)

In addition to quantifying the level of expenditures for social assistance, another key characteristic is their distribution across the population, in particular the incidence of benefits for the poorest quintiles.[23] Social assistance is intended for the poorest segments of a population, and if properly targeted, larger percentages would go to the poorest quintiles and no benefits to the richest ones. However, in the case of sub-Saharan Africa, the poorest quintile receives 11.3% of the benefits (average for the countries; the median is 8%), while the richest quintile receives 41.5% (average; median is 38.9%). The East Asia and Pacific region also shows a distribution biased toward the rich, with the poorest quintile receiving about 17% (average and median), much less than the richest quintile, with an average of 33.4% (median of 22%). The other world regions show a better distribution, with the poorest quintile receiving somewhat more than 30% (average and median), but the richest quintile still receives 10-16% of the benefits. These numbers suggest critical problems with the targeting of these programmes intended to help the poor and hungry.[24] In particular, countries in Africa seem to suffer the dual problem of both lower levels of expenditures overall (a median of about 0.9% of GDP) plus ineffective targeting of the poorest groups.

Table 3 Estimated expenditures for social assistance programs (billion dollars, average 2014–2018)

Billion USD	Total	CT+SP	School feeding	Public works	Food and in-kind	Health fee waivers	Other social assistance	Total excluding health fee waivers
AFR	20.2	12.6	0.9	2.8	1.3	0.5	0.6	19.7
EAP	164.9	47.1	0.8	13.8	9.1	92.3	1.7	72.5
(China)	146.7	39.1	0.0	13.8	5.4	88.4	0.0	58.3
ECA	72.8	59.1	0.3	1.5	0.6	5.8	5.5	66.9
LAC	84.8	44.2	3.9	1.2	2.9	25.9	6.6	64.2
MENA	24.7	10.5	0.0	0.0	9.5	3.7	0.9	21.0
SAR	40.3	4.9	1.5	6.4	24.5	2.2	0.7	38.1
(India)	35.3	1.3	1.4	5.8	24.0	2.2	0.6	33.2
Total	407.7	178.4	7.5	25.7	48.0	130.5	16.0	282.5
Total w/o China	260.9	139.2	7.5	12.0	42.6	42.0	16.0	224.2

Source: ASPIRE and WDI/WB.

21 The ASPIRE database covers 125 countries, 43 from Africa, basically from the sub-Saharan Africa (AFR), 15 from East Asia and the Pacific (EAP) (including China), 29 from Europe and Central Asia (ECA) (including Russia, Hungary, Ukraine), 22 from Latin America and the Caribbean (LAC), 10 from the Middle East and North Africa (MENA), and 6 from South Asia (SAR) (including India).

22 As a reference developing countries spent about 1.1 trillion dollars in social protection (on average for 2010–2017; based on IFPRI's SPEED database using data from the IMF). This is around 3.5–4.0% of their GDP for that period. Without China, the amount spent on social protection drops to about 916 billion dollars.

23 The estimates use all the annual household surveys for all the countries in the database (several countries have more than one household survey, and the years for each country vary; the average year of the surveys in the database is 2011). Benefit incidence is calculated as the percentage of benefits going to each quintile of the post-transfer welfare distribution relative to the total benefits going to the population (Sum of all transfers received by all individuals in the quintile)/Sum of all transfers received by all individuals in the population).

24 These are data from household surveys, which do not to capture the wealthier segments of the population well; therefore, what appears as the richest quintile in the survey may not be so in real life.

c) Brief consideration of expenditures related to COVID-19

The current pandemic is posing further challenges for fiscal accounts. Governments have implemented a variety of policies and investments in health, social protection, and support to employment and production, all of which require the use of a variety of unconventional monetary and fiscal instruments. As reported by the IMF policy tracker for governmental COVID-19 actions (covering most of 2020), developing and emerging countries made a strong additional fiscal outlay, surpassing 1.2 trillion dollars in 2020 (counting only additional public expenditures and until the time of reporting of the data), with 1.1 trillion dollars spent on non-health measures of social protection and maintenance of employment. However, not counting China, the amount is about 700 billion dollars, of which 680 billion dollars are for non-health measures of social protection and employment. Important questions to consider are whether these levels of expenditures can be sustained in the future, and how to manage the already accumulated debt related to the expanded expenditures. These additional COVID-19-related expenditures and debt will determine whether developing countries have the flexibility to increase public expenditures for SDG2 in the aftermath of the pandemic.

3) Banking system

Of the external flows discussed here, international development flows and public expenditures (discussed above) are mainly tied to governmental operations. However, the transformation of food systems to achieve the objectives of the 2030 Agenda will also require significant private investments from all operators in the food value chains. The internal cash flows from food operations (based on consumers' food purchases of some 7.7-8.3 trillion dollars, as mentioned above) can be expanded by loans from the banking system (which is discussed here) or by operations in capital markets (analysed in the next sub-section).

Table 4, based on FAOSTAT data, shows the total amount of loans provided by the banking sector to producers in agriculture, forestry, and fisheries (including household producers, co-operatives, and agro-businesses) and for all sectors (the average for 2014-2019, in current dollars). The previous sections presented finance data as annual flows; here, the information on loans is collected as annual stocks (namely the total of loans outstanding at a point in the year).

The total stock of loans is almost 42 trillion dollars in current dollars, of which about 22.9 trillion dollars are in developed countries, and some 18.9 trillion dollars in developing countries, or 7.3 trillion dollars if China is not included. The stock of loans for AFF is somewhat more than 1 trillion dollars; of this, developed countries represent about 530 billion dollars and developing countries account for about 473 billion dollars, or about 293 billion dollars if China is not counted.

Considering flows, there are no data on net disbursements (loans minus repayments of principal), but the

Table 4 Value of loans outstanding, total and for AFF (current dollars; average 2014–2019)

	Total Loans	Loans to Agriculture, Forestry, and Fishing (billion dollars)	% of AFF over Total Loans	AOI (median)
Africa	402.5	16.3	4.1	0.2
Asia developing	17043.6	427.9	2.5	0.4
(of which China)	11612.3	180.5	1.6	0.2
(of which India)	1201.3	143.2	11.9	0.7
LAC	1429.2	28.7	2.0	0.5
Oceania	995.7	93.3	9.4	1.4
Northern America & Europe	20978.8	404.4	1.9	1.1
Developing	18879.3	473.1	2.5	0.3
Developing w/o China	7267.0	292.6	4.0	0.3
Developed	22878.6	531.3	2.3	1.3
Total	41757.9	1010.2	2.4	0.4

Source: Author based on FAOSTAT.

change in stocks can be an indicator of those net flows. For total credit, the yearly average (2015-2019) change in stocks is about 1.6 trillion dollars globally, but the average for developing countries (not counting China) is only 87 billion dollars. The average annual change in loans for AFF during 2015-2019 is 24 billion dollars worldwide. The estimated flows for AFF in developing countries are around 14.2 billion dollars, or around 9.5 billion dollars if China is not included.[25]

Table 4 also shows the percentage of AFF loans as a share of total loans. In the case of developing countries without China, the coefficient is about 4% of total loans. However, as with public expenditures, a more revealing indicator of the importance of lending to the AFF sector is the AOI. For credit, this is calculated as the percentage of AFF credit in total credit, divided by the percentage of agricultural GDP in total GDP. The last column in Table 4 provides the median AOI for the countries in each region. As in the case of public expenditures, developing countries show much smaller AOIs than developed countries,[26] and values for Africa are lower than for other developing regions. In the case of India, the large share of AFF loans in total loans is also reflected in a higher AOI.

4) Capital markets

Capital markets at the global and national levels offer another source of external funds; given that interest rates are at the lowest level in more than 70 years, these markets are an appealing option. The focus here is on social and environmentally oriented investments, a potentially relevant source of funds for the transformation of food systems, considering the global trend toward investments that consider broader objectives along with financial returns.[27]

Definitions of these new investments are evolving, with some overlap among them (which means they cannot be added up across categories). The most common concepts are" environmental, social, and governance (ESG) investments," which encompass the broad category of sustainable and responsible finance; "impact investments," which try to generate a measurable positive social and environmental impact along with a financial return; and "thematic" bonds, such as green bonds, social bonds, and sustainability bonds, which are aimed, respectively, at specific environmental, social, or a combination of both objectives[28] (see KPMG 2019; and International Capital Markets Association [ICMA] 2020).

Because of the variations in definitions, data on the actual volume of operations vary depending on the source. Table 5 shows some estimates.

However, the largest shares of investments in those categories take place in developed countries, and the amounts oriented to agriculture and the transformation of food systems are small. For instance, the survey of impact investments in GIIN (2020) shows that only 8.1% of the funds (average 2018-2019) were allocated to food and agriculture.[29]

The challenge is to mobilise these resources for investments in support of the transformation of food sys-

Table 5 ESG, impact investment, and thematic bonds (billions of current dollars)

	Stock (Billions of USD)	Flow (Billions of USD)	Year of the estimate
ESG a/	30000	78	2018
Impact Investors b/	715	n/a	2020
Green Bonds c/	750	260	2019
Social Bonds d/	167	131	2020

25 The actual annual flow of loans for AFF may be larger, considering that some short-term credit may be extended and liquidated within the year and thus not affect stocks from one year to the next. There is no information about loans approved and disbursed by year. Nor are there aggregated data on total credit to other operators in food systems.

26 In Oceania, the values are dominated by Australia and New Zealand.

27 The FAOSTAT database includes estimates for Foreign direct investments (FDI) for Agriculture, Forestry and Fishing (AFF) and Food, Beverage and Tobacco (FBT). According to that source, developing countries received almost 2 billion dollars annually in FDI to AFF on average during 2014–2018, and about 2.7 billion dollars for FBT (but there are no data for some countries, such as China and Brazil, during that period). FDI for agriculture and agro-industries, in the aggregate, is part of the internal flows within food systems, but for individual countries they can be considered additional financing. They can be influenced by a variety of public policies as discussed in Díaz-Bonilla, Swinnen, and Vos (2021).

28 There are also other themed bonds, such as "blue bonds" for sustainable fisheries (see Fitzgerald, Higgins, Quilligan, Sethi, and Tobin-de la Puente 2020).

29 There are also several bonds issued by MDBs with agrifood components, but that money is then lent to developing countries as part of international development flows discussed above and, therefore, it is not included here to avoid double counting.

tems to achieve SDG2 and end hunger (more on this below).

D. MATRIX OF FINANCING

This section presents an indicative matrix of financing using the information from the previous two sections. The question is: Given the current levels of the different sources discussed in section C, is it possible to finance the costs identified in section B? To define a matrix that helps answer that question, some assumptions must be made about the percentage of financing from the individual financing sources for each group of interventions. Furthermore, it requires specification of the instruments to be utilised, because some of them may only be financed by public expenditures, while others could receive credit from the banking system or investments from capital markets.

Before turning to that specific exercise, it is important to note that global and regional aggregate savings are a macroeconomic constraint that cannot be ignored. Total available savings at the world level are about 21.6 trillion dollars (average of 2015-2019). Of this, 9.6 trillion dollars correspond to developing countries (but only 4.2 trillion not counting China); these savings are distributed very unevenly across regions. For instance, for sub-Saharan Africa, aggregate savings are only slightly more than 300 billion dollars. Global savings are the counterpart to the corresponding levels of world investments. Therefore, any proposal to increase investments in certain activities would require either that consumption be reduced, for some given level of global incomes;[30] or, that savings be redistributed toward the transformation of food systems, which would reduce investments in other activities, with the related impacts on those other sectors of the economy.

1) Indicative matrix

Table 6 assumes a matrix of financing with specific percentages by type of intervention and sources. It also shows the current values of flows of funds in those categories for developing countries calculated in the previous section (not counting China, to avoid its large values dominating the totals). The estimate for capital markets is a rough approximation, partially combining (to avoid double counting) the value of social bonds issued by developing countries (9.9 billion dollars), as surveyed in the Climate Bond Initiative and HSBC

Table 6 Matrix of incremental costs and financing, and reference flows, USD billions

	Average annual incremental investment cost	INTERNATIONAL DEVELOPMENT FLOWS	PUBLIC EXPENDITURES: AFF	PUBLIC EXPENDITURES: SOCIAL	PUBLIC EXPENDITURES: INFRASTRUCTURE	BANKING SYSTEM	CAPITAL MARKETS
AgR&D, Extension and ICT a/	6.6	1.3	5.3	0.0	0.0	0.0	0.0
Irrigation b/	3.8	0.8	1.1	0.0	0.0	1.5	0.4
Agricultural practices c/	4.4	0.9	0.9	0.0	0.0	2.2	0.4
Infrastructure d/	10.8	2.2	0.0	0.0	8.6	0.0	1.1
Gender and nutrition e/	5.0	1.5	0.0	3.5	0.0	0.0	0.0
Social protection f/	25.1	5.0	0.0	20.1	0.0	0.0	0.0
TOTAL (870 million lifted from hunger)	55.8	11.7	7.3	23.6	8.6	3.7	1.9
TOTAL (1 billion lifted from hunger plus expanded environmental interventions) g/	163.1	16.3	41.8	27.1	8.6	56.6	12.6
CURRENT FLOWS		11 to 12	86	293	n/a	9.5	9.9

Source: Author using data from section C. The following notes indicate what interventions from ZEF and FAO (2020) are considered in each group. (a) Agricultural R&D efficiency enhancement, Agricultural extension services, ICT-Agricultural information services, and Agricultural R&D; (b) Small-scale irrigation expansion in Africa; (c) Crop protection-Insects; Crop protection-Diseases; Crop protection-Weeds; Integrated soil fertility management; (d) Roads, Rail, Electricity; (e) Female literacy improvement, and Nutrition-specific interventions; (f) Social protection; Scaling up existing programs; Social protection; Establishing new programs; (g) Irrigation-Efficiency enhancement; Irrigation-Global large-scale expansion; Nitrogen-use efficiency; Food loss reduction; Soil-water management; Optimal crop planting and varieties (Adaptation); Soil carbon sequestration (Mitigation).

30 If there are enough idle resources at the global level so that world GDP can be enlarged, then savings and investments may be increased without affecting consumption.

(2021) (although they were not necessarily financing aspects of SDG2) and of the results for impact investment flows into agriculture (8.3 billion dollars in 2019), according to the survey in GIIN (2020).

For all interventions, it is assumed that international development flows and public expenditures will be present as sources of financing. However, for investments in irrigation and agricultural practices, it is assumed that banking systems and capital markets will also play a role, and that capital markets can also help finance some additional infrastructure.

The difference in estimated costs between lifting 870 million people and 1 billion people from hunger is due not only to the non-linearity in costs related to helping harder-to-reach groups of people but also to the expansion in environmental interventions required, mainly related to climate adaptation and mitigation (see the notes in Table 6 for the type of interventions considered in each block of estimates).

With this matrix of financing, policy options for each source are discussed to ensure that those resources can be expanded and mobilised to achieve SDG2 and end hunger.

a) International development flows

International development flows will have to increase by about 12-16 billion dollars above current levels (within the range suggested by IFPRI, IISD, and Cornell University [Laborde, Parent, and Smaller 2020]). The suggestion of this paper is that 2 billion dollars of that increase be allocated to support the ZHAF (discussed below). If total international development flows cannot be increased (because bilateral development aid may be limited by budgetary and political factors in donor countries, and net flows of non-concessional loans from MDBs may be constrained by their capital base and restrictive financial policies), this implies a reallocation of funds from other activities.

However, if bilateral aid can be increased and MDBs expand their capital, there would be no need to reduce support to other sectors. Even without capital increases, MDBs can negotiate with rating agencies to adjust risk parameters to allow for increased lending in the context of the pandemic (see Díaz-Bonilla 2020).

Developed countries can also consider using a percentage of their holdings of the new issue of SDRs in the IMF to support developing countries (the new allocation is expected to be about 650 billion dollars, of which about 60% goes to developed countries). For instance, during the current crisis, some countries with strong external positions have allocated part of their SDR holdings to expand the IMF's Poverty Reduction and Growth Trust (PRGT), which provides concessional loans to low-income countries.[31] At the recent 2021 spring meetings of the IMF and World Bank, there were discussions about developed countries donating or lending part of the SDRs that they do not need to support low-income countries, and some middle-income countries have asked to be included in that option.[32] Most of the conversation seems to focus on using those additional SDRs for debt reduction or for lending.

Here, an alternative use is suggested that would multiply the impact of those SDRs (or any developmental funds, for that matter) for broader objectives: as guarantees for issuing "zero hunger bonds" (explained later), for instance, allocating 2% of the new issuance to a guarantee fund. This would have the additional benefit of targeting the resources to a specific humanitarian objective, and would also help finance some policy interventions that address important environmental objectives (with the possibility of designing a subcategory of "zero hunger green bonds").

In general, international development funds should be used more strategically, namely to leverage and mobilise the other sources of financing discussed here, including, as mentioned, guarantees to de-risk the issue of zero hunger bonds or other socially or environmentally themed bonds. In addition, multilateral and bilateral organisations should better coordinate their own operations to avoid the fragmentation of relatively isolated initiatives and competition across international agencies at the country level.

Specific proposals: Increase by 15 billion dollars annually the international development funds dedicated to agricultural and rural development, food and nutrition security, and environmental aspects of food systems, which would imply somewhat more than doubling current levels. oroever, it is suggested to allocate part of those resources (2 billion dollars) to the

31 https://www.imf.org/en/About/FAQ/special-drawing-right

32 https://www.imf.org/en/News/Articles/2021/04/07/tr040721-transcript-of-imf-md-kristalina-georgievas-opening-press-conference-2021-s/pring-meetings

ZHAF (discussed later). Finally, it is proposed to allocate 2% of the future issue of SDRs of 650 billion dollars to create a fund to guarantee a new "zero hunger bond" to help finance the economic, social, and environmental interventions (and for the latter there may be a subcategory of "zero hunger green bonds") needed to achieve SDG2 and end hunger.

b) Public expenditures
Public expenditures for agriculture and rural development and for social assistance will both have to be increased by about 8.0-8.5%, with the objective of eliminating the risk of hunger for about 870 million people. If the objective increases to lifting 1 billion people from hunger, along with other climate mitigation and adaptation measures, then public expenditures in agriculture and rural development will need to expand by about 50% and in social assistance by close to 10%, in the aggregate and with the assumptions of the financial matrix. These increases can be achieved through different policy instruments and fiscal options.

Developing countries (not counting China) have total annual government outlays of some 3.7 trillion dollars, but only 86 billion dollars go to AFF. The budget allocated to social assistance has been estimated at about 260 billion dollars. However, indicators such as the AOI for agricultural expenditures or the percentage of social assistance expenditures in total GDP show that developing countries in general, and particularly in Africa and Asia (not counting China), devote comparatively fewer resources than other regions to those crucial interventions. Specific public expenditure reviews can help determine the adequacy of both the level and composition and the efficiency, efficacy, and equity of public expenditures dedicated to SDG2. Certainly, targeting could be improved in social and agricultural programmes, and the more than 50 billion in agricultural subsidies in developing countries (not counting China) could be repurposed (see footnote 20).

Moreover, better instruments can be utilised, such as some new enhanced social safety approaches. For instance, cash transfers have been evolving into more complete mechanisms to address social vulnerabilities. In the rural sector, they have begun to include poverty, nutrition, environmental, and productive payments (FAO 2017; De La O Campos et al. 2018). Recent work by the World Bank has expanded the framework for social inclusion, both in rural and urban settings, by defining multidimensional programmes with social safety nets, livelihoods and jobs, and financial inclusion (see Andrews et al. 2021). These instruments can help achieve zero hunger and also contribute to some important environmental objectives.

However, reallocating, better targeting, and repurposing public expenditures within a given agricultural and social budget envelope, even with better instruments, may not be enough to reach the levels needed for achieving SDG2 and ending hunger, and therefore, expenditures may have to be increased. In that case, the options are: (1) reallocation from other sectors, but within the same total budget envelope; and (2) an increase in expenditures (larger budget envelope) financed by monetary expansion (which may increase inflation), by additional public debt (which may lead to debt sustainability problems, requiring further debt relief schemes), and/or by increasing revenues. These options must be analysed at the country level; here the focus is on increasing revenues.

Several developing and emerging-economy countries will probably have to increase public revenues. One way to achieve this is by improving tax administration to reducing tax evasion. Furthermore, these countries should reassess the multiple exemptions to value-added and sales taxes: in several countries those exemptions represent an important loss of revenue, and because they apply to all sales, the exemptions do not help the consumers most in need, nor do they address challenges of nutrition or environmental sustainability.[33] Further, more progressive taxation of incomes and wealth will have to be implemented. Carbon taxes can also be considered.

Another consideration is that, in several countries, taxes on international trade are important both for fiscal purposes and because of their impact on domestic prices for consumers and producers. The adequacy of the taxes on international trade in terms of their fiscal, production, and consumption objectives will require a country-by-country analysis.

The ZHAF discussed below can help the interested countries to conduct the specific fiscal analyses involved in the reallocation, refocusing, and scaling up of public expenditures needed to support programmes

33 Taxing unhealthy and/or environmentally damaging food products has been recommended. Although these interventions may be useful to change the composition of food production and consumption, the amount of revenue collected may not be large. Also, the idea of using tax on unhealthy foods to subsidize healthy ones (and similarly for environmental purposes) could be considered, but must avoid specific earmarking of tax revenues, which fiscal best practices consider inadequate because of the budgetary rigidities and mismatches that such practice generates.

to end hunger, considering the constraints posed by the fiscal response to the pandemic.

Additionally, all countries, but particularly the developed ones that have greater influence on the operation of global financial markets, must be more active at the international and national levels to implement stronger controls on money laundering and tax havens that facilitate illegal financial outflows and tax evasion from developing countries. Moreover, proposals for a more unified system of taxation of international corporations, with an established formula to allocate the taxable base and a common minimum corporate tax, must be implemented.[34] These initiatives would help many developing countries to increase fiscal revenues that are now lost through corruption and tax evasion.

Specific proposals: Implement public expenditure and tax reviews as the basis for increasing and reallocating agricultural subsidies in developing countries (about 50 billion dollars without China); and for scaling up, better targeting, and redesigning social safety nets, using new and evolving cash transfer instruments that combine poverty, productive, nutritional, environmental, and financial inclusion components (such as the Cash Transfers Plus analysed by FAO or the evolving instruments of social inclusion considered by the World Bank). To this end, it is also suggested that the AOI of AFF expenditures be increased to at least 0.5 and expenditures for social protection be increased to at least 2% of total GDP in developing countries. Finally, revenues in developing countries should be strengthened through better tax administration and the revision of sales, income, wealth, and trade taxes, and by implementating international initiatives to control corruption, tax evasion, and other practices that erode those countries' tax bases. Carbon taxes can also be considered.

c) Banking system

If irrigation and the adoption of improved agricultural practices are to be financed in part by loans from the banking system, as assumed in Table 6, then credit to the agricultural sector in developing countries (not including China) will have to increase (some 40% in flows in the central estimates of 870 million people avoiding hunger, as shown in Table 6). For the banking sector to play this role, the systemic barriers that limit the supply of financial services for agriculture, small farmers, and the poor and vulnerable (women, disadvantaged ethnic groups, and youth) must be addressed. Detailed country-level analysis of banking system operations will be needed to assess whether these systems can finance the activities need to achieve SDG2, while adequately performing the triple function of operating the payment systems, intermediating between savings and investments, and providing risk-management instruments.[35]

This country-focused analysis should consider the following aspects related to agricultural credit and financial services. First, the adequacy of the overall macroeconomic and regulatory framework. Second, what is the origin and use of the funds that are to be intermediated (such as deposits; budget allocations by the government; monetary sources such as rediscounts by the monetary authorities; regulatory mandates to lend to the agricultural sector; loans from international organisations; and others). In particular, consideration could be given to employing an updated version of the unconventional monetary policies that sustained agrifood development in the 1960s and 1970s, implemented by what have been called "developmental central banks" (see below; a general discussion is found in Díaz-Bonilla 2015).

The third component of the analysis should look at what type of banking and financial institutions can intermediate those funds (and perform the other two functions of operating the payment systems, and providing risk-management instruments, as mentioned). A wide variety of formal and informal operators provide loans, manage savings, and offer other financial services to the rural population and the agrifood system in general, and each type has its own advantages and disadvantages. In this context, it is relevant to reconsider the role of public development banks with an agricultural orientation, which were dismantled in many developing countries during the 1990s, but whose operations are now being reconsidered.[36] Public funds or public institutions that offer loan guarantees to banks are also important for expanding the

34 Those proposals build on options analyzed by the OECD in its work on "based erosion and profit shifting" (see https://www.oecd.org/tax/beps/flyer-inclusive-framework-on-beps.pdf).

35 What follows is based on Díaz-Bonilla (2015); Díaz-Bonilla and Fernández-Arias (2019); Díaz-Bonilla, Fernández-Arias, Piñeiro, Prato, and Arias (2019). Those studies have a more detailed discussion of the issues mentioned here.

36 An example was the November 2020 "Finance in Common Summit" of Public Development Banks (PDBs), co-organized as a joint initiative of the International Development Finance Club (IDFC), the World Federation of Development Finance Institutions (WFDFI), SAFIN, IFAD, and the government of France (see https://www.ifad.org/documents/38714174/42142599/fic_statement.pdf/6a6fcfe1-6614-7786-c69a-743df3dcd5e6).

coverage of credit to small farmers and SMEs in food value chains, particularly to women, vulnerable ethnic groups, and youth.

The fourth component is to consider financial instruments. Starting with credit, longer-term loans face agriculture-sector-specific problems, such as the dispersion and small scale of customers and the presence of covariant risks. They are also affected by macroeconomic volatility, and regulations that are designed for the urban sector and for activities with more regular cash flows than the agricultural sector, as agriculture requires flexible disbursement and payment schemes aligned with the rhythms of agricultural activity. Innovative insurance schemes, technical assistance, and better weather and market information can mitigate some of the risks in agriculture. However, in any case, the development of credit for long-term investment may require funding from public fiscal or monetary sources (as suggested above and discussed below in greater detail), or intermediation in capital markets. Supply-chain and value-chain lending offer a flexible form of financing that can help to include small farmers; input and equipment suppliers should also be considered as potential vehicles for lending to small and family farmers.

Beyond the obstacles to credit, there is a dearth of other financial products and services needed by small farmers, rural populations, and SMEs. This is true both on the financing side (such as leasing, warrants, and discount of invoices, all of which require the adaptation of regulations and operational mechanisms) and on the payments and savings side (for instance, simplified checking and savings deposits, which are an important risk mitigation tool for rural households). In all of these cases, digital technology can reduce transaction costs and generate more information about potential customers, lowering risk for financial institutions.

As noted above, in the past many developing countries operated with what were called developmental central banks, which offered loans (rediscount lines) to public agricultural banks (and also private financial institutions) with specific purposes, such as providing credit to agricultural producers. This combination of rediscounts by central banks channelled through agricultural banks was eliminated in many countries during the 1980s and 1990s in the face of dual concerns that the increases of money supply (generated by the rediscounts) were fuelling inflation and that public banks suffered from a variety of problems (corruption, mismanagement, bias toward large producers, crowding out private sector financial options, and so on). However, in the context of the 2008 global recession and the current pandemic, central banks, mainly in developed countries, have revived the use of those dedicated lines of credit to buy both public and private credit instruments (under the name of quantitative easing).[37] That expansion of money supply is being made in the context of monetary programmes that include inflation targets. At the same time, several public agricultural banks have been reformed and now operate more efficiently and with developmental objectives (Díaz-Bonilla 2015). Those operations must consider the financial needs of women, minorities, and youth.

Specific proposals: Reactivate the role of developmental central banks using rediscounts to offer credit to small farmers, rural populations, and SMEs in food value chains (within a consistent monetary programme that maintains control of inflation). In addition, public development and agricultural banks could be revitalised and modernised (with incentives, performance metrics, and controls to avoid problems experienced by these institutions in the past) to increase loans, including environmentally linked loans (supported by the central banks' discounts) and offer other financial services to small farmers, rural populations, and SMEs in food systems, with particular consideration for women, vulnerable ethnic minorities, and youth. Finally, the AOI for agricultural credit in developing countries could be increased (for example, to at least 0.5).

d) Capital markets

With this matrix of funding (and recognising the very preliminary value of the estimates in Table 6), capital market operations may have to increase by about 20% over current estimated levels to lift 870 million people from hunger by 2030 (it would likely have to increase by almost 130% if the objective is to lift about 1 billion people from hunger and achieve other environmental objectives in SDG2).[38] This will require developing a robust pipeline of investable opportunities (including individual projects, impact investment funds, and/or thematic bonds) with the adequate profile of risk/reward to attract investors, and clear, measurable, and

37 The U.S. Federal Reserve operated as a developmental central bank to help the U.S. economy in the 1930s (Fettig 2008).
38 Expanding the focus further to other SDGs would lead to larger investments from capital markets.

monitorable impact objectives, aligned with achieving SDG2 and ending hunger.

A specific unit could be set up at the international level to link private capital with investable opportunities for small farmers and rural populations in social and environmentally relevant activities. In this case, the objectives of zero hunger, doubling productivity, and environmental sustainability can be achieved with adequate technologies. Díaz-Bonilla et al. (2018) presented a proposal for a project preparation/incubation/acceleration facility, based on CGIAR technologies and focusing on small farmers, and leveraging the presence that the CGIAR centres have in more than 100 developing countries, where they work with a variety of NARIs.[39]

The project preparation/incubation/acceleration facility would carry out a series of key actions (see Díaz-Bonilla et al. 2018). First, individual opportunities need to be identified and business plans prepared. They generally will be small- and medium-scale projects involving small and family farms; these are complex and difficult to structure. Site-specific technological options and marketing opportunities must be analysed. Second, those small projects must be aggregated and structured (as a different type of investable vehicle), with adequate rates of return and risk profiles, and with value sizes that compensate investors for the transaction costs and due diligence requirements. Third, both the small farmers and the investors will require technical assistance, particularly in relation to sustainable technologies; this can be based on the work of the CGIAR centres and participant NARIs. Fourth, metrics for the impacts desired must be defined and monitored. All of those activities require a dedicated cadre of specialists.

This facility can also support enhanced environmental lending by the agricultural public banks mentioned in the section on banking.

The facility can be structured as a revolving fund, where the preparation costs are in total or in part reimbursed by the appropriate private and/or public partner after the investment opportunity materialises. With this mechanism, the facility could mobilise funds that will be a larger multiple of the resources allocated to the facility. International development funds, as well as some national public expenditures, can be used more strategically in this facility as blended finance with private sector funds and to de-risk investments.

As discussed above, thematic bonds offer another type of instrument in capital markets. Although these can finance private sector operators,[40] the focus here is on their potential for funding public sector operations. Additional funds mobilised through this instrument are therefore considered as part of public expenditures, and do not appear as a separate line in capital markets in Table 6. In particular, international development funds could be used to design and reduce the risk of zero hunger bonds issued by developing countries.[41]

The specific design will have to be discussed with potential private and institutional investors, but some features to consider are discussed here. The “zero hunger bond” can be a consol or perpetual bond;[42] issued in dollars; paying an adjustable rate with a cap (say 5%[43]); and callable, with call protection (for example, until 2050). As mentioned, 2% of the new allocation of SDRs of 650 billion dollars (13 billion dollars) can be assigned to a fund, which could be set up within the IMF, to guarantee the interest rate payments of zero hunger bonds issued by countries with programmes to end hunger as part of the Zero Hunger Alliance discussed below. Other official development aid and private philanthropic funds could be utilised as well to guarantee the interest payments and thus eliminate country risk for the countries participating in the global programme to eliminate hunger.

This use of international development funds will greatly increase their impact: for instance, 13 billion dollars can guarantee an issuance of up to 260 billion dollars

39 More recently, there have been other similar ideas regarding the need for an institutional device to link investable opportunities and investors (see, for instance, Millan, Limketkai, and Guarnaschelli [2019] and Finance for Biodiversity Initiative [2021]).

40 An example is a social bond issued by the private firm Danone for 500 million euros in 2018, which included some agricultural aspects (iiLAB 2018).

41 These may be mainly an option for developing countries that do not have access to highly concessional loans or grants. MDBs may also find it useful to issue long term zero hunger bonds to finance developing countries (but then the intermediation charges will have to be adjusted accordingly).

42 Alternatively, 100-year bonds can be considered, with payment periods during the last 10 years.

43 The cap considers that the average nominal yield since 1953 for US 10-year bonds has been 5.7% (4.4% since 1990); average consumer inflation in the United States has been about 3% since 1913 (2.4% since 1990); and the average real interest rate for the last 200 years has been 2.6%, but it has been declining in the last 100 years (see for instance, Schmelzing 2020). The yield for the 10-year inflation-adjusted bond for the period 2003–2021 has been 0.93% (data from the U.S. Federal Reserve; https://fred.stlouisfed.org/series/DFII10).

in zero hunger bonds (under the assumptions in the footnote[44]). As mentioned, this approach, in addition to providing resources for a specific humanitarian objective (zero hunger), would also help finance agricultural technologies and other environmental interventions that address crucial objectives related to climate change mitigation and adaptation (therefore, some of them could be zero hunger green bonds). Further, it will offer a safe asset that can help absorb some of the excess liquidity in global capital markets.

Certainly, the financial scheme suggested here can also be utilised for special bonds with other purposes, such as financing pandemic-related expenditures (for example, a "COVID reparation bond").

Specific proposals: Create a project preparation/incubation/acceleration facility to structure productive opportunities for small farmers into investable opportunities for impact investors, using economic, social, and environmentally sound technologies with the support of One CGIAR and NARIs. In addition, countries participating in the ZHAF (see below) could be supported through the design, guarantee (using 2% of the new allocation of SDRs and perhaps other public funds), and launch of a new type of social and environmental bond, called a zero hunger bond, as a perpetual (or long-dated) bond, with capped adjustable rates. Both proposals can be operationalised as part of the work of the ZHAF discussed below.

2) An alternative financial matrix based on expanding public sector instruments

The financing matrix presented in Table 6 is just an example, and different percentages of financing by sources can be considered. Those percentages depend on the specific conditions in individual countries and on the instruments to be utilised. For instance, a government may decide to scale up the instrument that combines the use of cash transfers based on poverty considerations with grants linked to productive activities, environmental sustainability, and similar activities. In that case, the additional costs of improved technologies will be financed by grants from the public sector (as suggested in IFPRI, IISD, and Cornell University [Laborde, Parent, and Smaller 2020]), instead of loans from the banking system.

Scaling new social assistance and productive programmes, which are based on public expenditures, would significantly reduce the need for bank financing. In this scenario, the use of capital markets will depend on the investable vehicle; there may be a greater need for thematic bonds, including the new zero hunger bond, issued by governments (or by MDBs that then lend to governments) to finance public sector expenditures.

E. THE NEED FOR COUNTRY-BASED INSTITUTIONAL ARRANGEMENTS

The quantitative estimates and the financing matrix discussed above suggest that, in the aggregate, additional resources are available that could be used to lift 870 to 1 billion people from hunger by 2030. Several adjustments, improvements, and specific proposals were presented for each of the financing sources analysed.

However, even if the resources exist and the potential for mobilising them effectively can be increased with the adjustments and proposals recommended, they can only be transformed into solid programmes to end hunger and achieve SDG2 if individual countries are willing and capable. The potential sources of financing and whether they are sufficient cannot be judged only at the aggregate level; they also need to be assessed in each individual country.

Further, achieving SDG2 and eliminating hunger is not only a matter of financing the necessary interventions but also requires that a country and its authorities have the political will and the institutional capacity to carry them out. Institutionally weak governments cannot design and finance the programmes and coordinate the work of their own ministries and agencies and of the international organisations operating in their countries. Such countries could benefit greatly from the establishment of institutional mechanisms at the country and international support to help design, finance, and implement national programmes. The fiscal constraints entailed by the public responses to the current pandemic increase the need for these country-based arrangements.

Therefore, implementing institutional mechanisms at the international and national levels is recommended

44 A perpetual bond with a floating coupon with a cap of 5%; the default rates of the interest payments that have to be paid by the guarantee fund are similar to those of the IMF or the World Bank; and that the erosion that those payments inflict on the guarantee fund are covered by additional international public money. If the guarantee fund is not replenished, the total amount of bonds to be guaranteed will depend on the assumptions about the default rate, and whether the guarantee is calculated against the cumulative value of such erosion for a certain time frame, or some other formula. For example, a default of 1% per year on the original value of the guarantee fund, in 50 years would have cut the value of the guarantee fund by half.

to coordinate the activities needed to achieve SDG2, and, in particular, those focusing on ending hunger, as analysed immediately.

F. THE ZERO HUNGER ALLIANCE & FUND

1) Introduction and background

This section discusses the creation of a public-private institutional arrangement, called the Zero Hunger Alliance & Fund (the Alliance) to support, financially and operationally, those individual countries that want to participate in a global programme to achieve zero hunger by 2030.[45]

The idea of a fund dedicated to eliminating hunger has been proposed by different international leaders. The proposal outlined here builds on the idea of a Zero Hunger Fund, which has been suggested by Action Track One of the UNFSS.[46]

The proposal in this section is based on the premises outlined in section E, namely that although it was shown that on aggregate there seem to be sufficient sources of funding that can be mobilised, real availability must be assessed at the country level, and that achieving SDG2 and eliminating hunger requires that a country and its authorities have sufficient political will and institutional capabilities. Therefore, adequate institutional coordinating mechanisms are needed to support countries committed to ending hunger to design the programmes, mobilise the resources available to them, and implement the interventions needed.

However, what would those potential global institutional and financial arrangements for ending hunger be? The following brief review of three experiences can illuminate the options: the GAFSP, the PRSPs, and GAVI, the Vaccine Alliance.

2) Lessons learned

a) Global Agriculture and Food Security Program (GAFSP)

The creation of another fund to directly finance ending hunger by 2030 would lead to questions about how it would fit with other existing initiatives. The proposal for GAFSP's creation led to discussions about the complementarities (or lack thereof) with other financial mechanisms, such as the World Food Program (although the WFP is intended largely for emergencies), and IFAD (which offers loans and grants to support small farmers mainly in poor countries). Furthermore, the World Bank's mission statement calls for ending extreme poverty (which is usually defined by a minimum-calorie poverty line, below which there is hunger) and other MDBs have similar objectives. Within that framework of potentially overlapping missions, GAFSP was able to establish a niche as a grant-maker in support of small farmers.

There are also other considerations, highlighted by the experience of GAFSP. For instance, what size should the fund be? Evaluations of GAFSP have noted that the demand for its grants far exceeds the size of the fund, and the gap is too large to be filled (LTS International.2018). GAFSP tries to place its operations within the more general agricultural programmes in the countries where the grants are approved and has also been able to mobilise additional funding in its projects. Following the model of directly financing interventions with grants, given their relatively small size and dispersion, it would be difficult to achieve the scale needed to end hunger. On the other hand, using the funds to mobilise a multiple of the potential additional resources available may be more promising, as discussed below.

Another issue is where to locate institutionally. Eventually, GAFSP was placed within the World Bank, which acts as host, trustee, and is one of the implementing partners (which also include other MDBs and UN agencies). Another institutional consideration is the mechanism of coordination with the other institutions and funds mentioned above. The proposal discussed below takes those concerns into consideration.

b) Poverty reduction strategy papers or programs

The experience of the PRSPs also offers relevant lessons. They were initiated by the World Bank and IMF in September 1999 as a mechanism for linking debt relief with poverty reduction under the Enhanced Heavily Indebted Poor Countries Initiative (HIPC). The PRSPs were also expected to become a framework for

45 In what follows the word "Alliance" (capital letters) refers to the institutional arrangement suggested, while "alliance" (lower case letters) denotes the country partnerships.

46 See Action Track 1: Ensure Access to Safe and Nutritious Food for All. Potential Game Changing and Systemic Solutions: An Initial Compilation" Submitted to the UN Food Systems Summit Secretariat, 19 February 2021. It recommends channeling "private sector resources to investments to end hunger by 2030," with matching funds from governments and other donors, with the objective of creating a fund of some 4–5 billion dollars. Contributions from the private sector are assumed to come mainly from food companies (0.2030% of their profits), allowing them to repurpose their corporate social responsibility (CSR) efforts. Food companies have not, in general, supported the idea, arguing that it would be a corporate social responsibility (CSR) tax.

concessional and non-concessional development support from other multilateral and bilateral agencies in low-income countries. They were based on five core principles for the programmes: country-driven; comprehensive; based on a long-term perspective; results-oriented; and partnership-oriented (World Bank and IMF 2005).

The experience of the PRSPs showed:

- the need for country-initiated and country-owned, medium-term, integrated programmes, as a coordinating mechanism for the work of the national ministries and agencies and for support from the international community;
- as well as the limitations of the PRSPs being anchored in specific international organisations, with their own institutional requirements.[47]

c) GAVI. The Vaccine Alliance[48]
GAVI is an independent public-private partnership and multilateral funding mechanism that is not housed in any of the international organisations. First, this frees its operations from idiosyncratic institutional requirements. Moreover, being an independent partnership, it can work with all public international and national organisations, as well as the private sector. In fact, its operating model is based on partnerships with a variety of public and private organisations.

Second, GAVI has a simple, measurable, and well-defined objective (help countries to reach a specific number of people vaccinated) and uses streamlined instruments and delivery mechanisms.

Third, it applies its funds strategically to mobilise a variety of local and international financial resources, thus multiplying its impact.

Fourth, the work depends on the initiative of a country that decides to participate in the Vaccine Alliance and is based on that country's specific programme. However, the Alliance offers technical and financial support to design and implement the programme, while helping with a flexible architecture of public and private partnerships, national and international, that are needed to carry it out.

Fifth, its governance is also streamlined, with a Board that represents the main countries and organisations contributing funds and a limited Secretariat (with a chief executive officer, and a team of country responsible officers, who work directly with countries to implement programmes according to the agreements reached).

Sixth, in addition to the traditional funding source of periodic pledges, it has a financing mechanism that uses donor funding commitments to back the issuance of special bonds in capital markets to finance the vaccination programmes.

The proposal presented here considers the key lessons from the three experiences analysed, including: (1) the importance of focusing on country-owned, medium-term, integrated programmes; (2) the need for clear and measurable objectives; (3) the strategic use of scarce development funds to mobilise far larger financial resources; and (4) the design of flexible public-private institutions with strong coordinating and operational capabilities.

At the same time, it is important to monitor operations to ensure that the focus on a single objective does not end up diverting scarce human and financial resources in developing countries from other relevant objectives. Therefore, the need to have country-owned, integrated programmes that set the framework.

3) Key Characteristics of a Zero Hunger Alliance & Fund
Based on these lessons, the proposed ZHAF would have the following characteristics and objectives (see more details in the Annex):

- It focuses on a clearly measurable objective: eliminating hunger by 2030.
- It is an independent public-private institution,[49] with a dedicated fund and with personnel seconded from international organisations focusing on poverty, food security, and nutrition issues, who will work in close cooperation with local teams of partners in the participating countries, and as such form an Alliance.
- There will be a dedicated fund to (a) cover the operational costs (but not the salaries of the seconded personnel); (b) hire technical and operational

47 See some of those points in World Bank and IMF (2005).
48 https://www.gavi.org/our-alliance/about
49 Other options would be to insert the Zero Hunger Alliance and Fund into an existing institution, such as the World Bank, or in a specific consortium of institutions, such as FAO and IFAD, created for that purpose. These options can have the benefit of accelerating the start of the work, but also the potential cost of slowing the subsequent operation due to idiosyncratic institutional requirements and/or by being seen as “dominated” by some specific institutions, when its role is to support countries to coordinate a variety of partnerships, national and international, public and private.

expertise needed to support the countries in defining the programmes and mobilising the human, financial, and institutional resources to carry them out; (c) de-risk some financial operations to mobilise private capital (such as the issuance of zero hunger bonds); and (d) eventually, finance some interventions directly. The largest value in the use of those funds will be for (c), but the most important use, operationally, will be for (b).

- The funding will come from the additional international development funds (as discussed above, about 2 billion dollars), plus an effort to mobilise private funds, with the target of obtaining commitments from at least 50 companies (from food and other sectors) to donate about 10 million dollars each (these companies will be recognised as Champions of the Zero Hunger Alliance). Combined, those funds would amount to 2.5 billion dollars per year.
- In addition, 2% of the planned allocation of SDRs (or 13 billion dollars) will be utilised to design, launch, and guarantee zero hunger bonds (and zero hunger green bonds) issued by countries with programmes to end hunger as part of the Zero Hunger Alliance. Depending on how the guarantees are structured and maintained over time, they could multiply the value of the SDRs directly allocated to this initiative by a factor of more than 10.
- Most of these funds will be leveraged to mobilise the other sources of financing discussed above (public budgets, banking systems, and capital markets) at the country level.
- The Alliance will support financially and operationally those individual countries that sign agreements to join this global partnership to end hunger by 2030, helping them to identify the target population, define the specific institutional, programmatic, and instrumental components, mobilise the necessary funding, and structure the partnerships needed to carry out the programmes to end hunger by 2030.
- In particular, it is suggested to expand the use of the new instruments that combine cash transfers based on poverty with additional productive, nutritional, environmental, and financial inclusion components.

Table 7 Summary of Proposals

TOPICS	PROPOSALS
International Development Flows	*Increase by 15 billion dollars annually the international development funds dedicated to agricultural and rural development, food and nutrition security, and environmental aspects of food systems, which would imply about doubling current levels.
	*Allocate yearly 2 billion dollars of the additional 15 billion dollars to the Zero Hunger Alliance & Fund.
	*Allocate 2% of the future issue of Special Drawing Rights (SDRs) of 650 billion dollars to offer guarantees for a new “zero hunger bond” to help finance the economic, social, and environmental interventions (and for the latter there may be a subcategory of “zero hunger green bonds”) needed to achieve SDG2 and end hunger. These instruments can be perpetual or very long-termed bonds, with an adjustable coupon.
Public Budgets	*Implement public expenditure and tax reviews to increase and reallocate agricultural subsidies in developing countries (about 50 billion dollars, without China) and scale up, better target, and redesign social safety nets using new and evolving cash transfer instruments that combine poverty, productive, nutritional, environmental, and financial inclusion components (such as the Cash Transfers Plus analyzed by FAO or the evolving instruments of social inclusion considered by the World Bank).
	*Increase the Agricultural Orientation Index (AOI) of expenditures for agriculture, forestry, and fisheries (for example, to not less than 0.5) and social protection expenditures as percentage of GDP (for example, to at least 2%).
	*Revenues in developing countries should be strengthened by better tax administration and revision of sales, income, wealth, and trade taxes, and by implementation of international initiatives to control corruption, tax evasion, and other practices that erode those countries’ tax bases. Carbon taxes can also be considered.
Banking Systems	* Reactivate the tools of the “developmental central banks,” using rediscounts to offer credit to small farmers, rural populations, and SMEs in food value chains (within a consistent monetary program that maintains control of inflation control).
	*Revitalize and modernize public development and agricultural banks (with incentives, performance metrics, and controls to avoid the problems of the past in this type of institution) to increase credit (supported by central bank discounts) and offer other financial services to small farmers, rural populations, and SMEs in food systems, with particular consideration for women, vulnerable ethnic minorities, and youth.

	*Increase the AOI of agricultural credit to at least 0.5.
Capital Markets	*Create a project preparation/incubation/acceleration facility to structure productive opportunities for small farmers into investable opportunities for impact investors, using economic, social, and environmentally sound technologies with the support of One CGIAR and national agricultural research institutes (NARIs) and partners in more than 100 developing countries.
	*Support countries that participate in the Zero Hunger Alliance & Fund with the design, guarantee (using 2% of the new allocation of SDRs and other public funds), and launch of a new type of social and environmental bond, called a “zero hunger bond.”
	Both proposals can be operationalized as part of the work of the Zero Hunger Alliance & Fund.
Zero Hunger Alliance &Fund	*Create a public–private international institution, with a dedicated fund, to organize country-based alliances to eliminate hunger by 2030.
	*It will function with personnel seconded from international organizations dedicated to poverty, food security, and nutrition issues, who will work in close cooperation with local teams of partners in the participating countries—and as such form an Alliance.
	*There will be a dedicated fund to (a) cover the operational costs (but not the salaries of the seconded personnel); (b) hire the additional technical and operational expertise needed to support participating countries in defining the programs and mobilizing the human, financial, and institutional resources to carry them out; (c) de-risk some financial operations to mobilize private capital (such as the issuance of zero hunger bonds); and (d) eventually, finance some interventions directly.
	*The funding will come from the additional international development funds (about 2 billion dollars per year), plus a mobilization of private funds (a target of 500 million per year).
	*In addition, 2% of the planned allocation of SDRs will be utilized to design, launch, and guarantee zero hunger bonds (and zero hunger green bonds).
	*The Alliance will support financially and operationally those individual countries that sign agreements joining this global partnership to end hunger by 2030, helping them identify the target population, define of the specific institutional, programmatic, and instrumental components, mobilize the necessary funding, and structure the partnerships needed to carry out the programs to end hunger by 2030.

Source: Author.

The institutional arrangement outlined here has several advantages, including that (1) it supports the country members of the Alliance in implementing country-owned, country-coordinated, integrated programmes; (2) it focuses on a single and measurable objective (ending hunger by 2030) but, given the type of agricultural technologies and environmental interventions supported, it also contributes to crucial objectives related to climate change mitigation and adaptation; (3) it mobilises a significantly larger volume of funds than those directly allocated to the Alliance; (4) it reduces the risks of creating another permanent international bureaucracy by relying on temporary secondment from existing organisations; and (5) it has a flexible public-private institutional structure.

G. SUMMARY OF PROPOSALS

It should be noted that the adjustments in the operation of banking systems discussed above also address the main issues raised by the following proposals in the Action Tracks: “Establish a catalytic SME financing facility to transform food systems”; “Global matching investment fund for small-scale producers’ organisations”; “Invest in the future: Making food systems finance accessible for rural people”; “Public development bank initiative to catalyse green and inclusive food system investments”; and “Blended financing mechanism to small projects/initiatives locally owned by women and youth along agricultural value chains.”

Furthermore, the preparation/incubation/acceleration facility can help with other financial proposals from the Action Tracks, such as a “$200m climate smart food systems impact investment fund”; and a “Soils investment hub.”

The creation of a ZHAF is also suggested, based on the idea of a dedicated fund to end hunger presented by Action Track One, with the specific objective of supporting institutionally and financially those countries that want to join a global partnership to end hunger. The proposed zero hunger bond (or zero hunger green bonds) can also be an important component of the financing mobilised by the Zero Hunger Alliance and Fund.

H. CONCLUSION

This paper has analysed the costs and potential financial mechanisms for achieving SDG2 and ending hunger, and made a series of specific proposals to reach those objectives. If implemented, those proposals would lead to an additional 15 billion dollars in development funds annually, may mobilise an additional 230 billion dollars in public expenditures per year in developing countries (not including China) for sustainable agricultural and rural development and social assistance, may increase the loan portfolio for agriculture, forestry, and fisheries (in developing countries not counting China) by about 195 billion dollars (a stock), and would support the issuing of up to 260 billion dollars in zero hunger funds (depending on how the guarantees are structured). The proposals also support the creation of a ZHAF, with 2.5 billion dollars per year and the operational capacity to mobilise the resources mentioned above in support of country-owned and country-coordinated integrated programmes to end hunger by 2030. The options discussed also contribute to the implementation of other financial proposals considered by different Action Tracks, in particular the proposal of a Zero Hunger Fund from Action Track One. It is hoped this paper can contribute to the debate on how to achieve the SDGs and end hunger in a transformed, improved global food system.

REFERENCES

1. Andrews, C., A. de Montesquiou, I. Arévalo Sánchez, P. Vasudeva Dutta, B. Varghese Paul, S. Samaranayake, J. Heisey, T. Clay, and S. Chaudhary. 2021. The State of Economic Inclusion Report 2021: The Potential to Scale. Washington, DC: World Bank.
2. Amundi Asset Management. 2020. Social Bonds: Financing the Recovery and Long-Term Inclusive Growth. Investment Insights Blue Paper (Nov.)
3. Climate Bonds Initiative. 2019. Green Bonds: Global State of the Market 2019.
4. Climate Bond Initiative. 2021. Sovereign Green, Social, and Sustainability Bond Survey: The Ultimate Power to Transform the Market. Climate Bonds Initiative and HSBC.
5. Díaz-Bonilla, E. 2015. Macroeconomics, Agriculture, and Food Security: A Guide to Policy Analysis in Developing Countries. Washington, DC: International Food Policy Research Institute. http://dx.doi.org/10.2499/9780896298590
6. Díaz-Bonilla, E. 2020. "Fiscal and Monetary Responses to the COVID-19 Pandemic: Some Thoughts for Developing Countries and the International Community." In COVID-19 and Global Food Security, eds. J. Swinnen, and J. McDermott, 98–101. Washington, DC: International Food Policy Research Institute. https://doi.org/10.2499/p15738coll2.133762_22
7. Díaz-Bonilla, E., and E. Fernández-Arias. 2019. "Políticas Públicas y Mercados Financieros para el Desarrollo Rural y Del Sistema Agroalimentario en América Latina y el Caribe." LAC Working Paper 2, International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/p15738coll2.133331
8. Diaz-Bonilla, E., E. Fernández-Arias, V. Piñeiro, B. Prato, and J. Arias. 2019. "Foro de Análisis Financiamiento e Inclusión Financiera para el Desarrollo Agropecuario, Rural y de Sistemas Alimentarios en América Latina y el Caribe: Documento Resumen." LAC Working Paper 5, International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/p15738coll2.133448
9. Díaz-Bonilla, E., A.M. Loboguerrero, L. Verchot, E. Viglizzo, and A. Mirzabaev. 2018. Financing a Sustainable Food Future. T20 Argentina: Food Security and Sustainable Development Task Force Brief. Washington, DC: International Food Policy Research Institute. https://t20argentina.org/wp-content/uploads/2018/06/TF3-3.5-Task-Force-3-FINAL-v4-EDB-revised-after-peer-review.pdf
10. Díaz-Bonilla, E., J. Swinnen, and R. Vos. 2021. "Financing the Transformation to Healthy, Sustainable, and Equitable Food Systems." In Global Food Policy Report 2021: Transforming Food Systems after COVID-19, 20–23. Washington, DC: International Food Policy Research Institute.
11. Fan, S., ed. 2008. Public Expenditures, Growth, and Poverty in Developing Countries: Lessons from Developing Countries. Baltimore: Johns Hopkins University Press.
12. FAO (Food and Agriculture Organization of the United Nations). 2012. The State of Food and Agriculture 2012: Investing in Agriculture for a Better Future. Rome.
13. FAO (Food and Agriculture Organization of the United Nations). 2017. Cash+: FAO's Approach. Rome. http://www.fao.org/3/i7864e/i7864e.pdf
14. Fettig, D. 2008. "The History of a Powerful Paragraph." Banking and Policy Issues Magazine. Minneapolis: Federal Reserve Bank of Minneapolis.
15. FOLU (Food and Land Use Coalition). 2019. Growing Better: Ten Critical Transitions to Transform Food and Land Use. Global Consultation Report of the Food and Land Use Coalition.

16. Finance for Biodiversity Initiative. 2021. Greening Sovereign Debt: Building a Nature and Climate Sovereign Bond Facility.
17. Fitzgerald, T.P., P.R. Higgins, E. Quilligan, S.A. Sethi, and J. Tobin-de la Puente. 2020. "Catalyzing Fisheries Conservation Investment." Frontiers in Ecology and the Environment 18(3): 151–158.
18. GIIN (Global Impact Investing Network). 2020. Annual Impact Investor Survey 2020. 10th Edition. New York.
19. Laborde, D., M. Parent, and C. Smaller. 2020. Ending Hunger, Increasing Incomes, and Protecting the Climate: What Would it Cost Donors? Ceres2030: Sustainable Solutions to End Hunger. Washington, DC: International Food Policy Research Institute; Winnipeg, Canada: International Institute for Sustainable Development; Ithaca, New York: Cornell University.
20. iiLab (Impact Invest Lab). 2018. The Social Bond Market: Towards a New Asset Class? Paris.
21. ICMA (International Capital Markets Association). 2020. Social Bond Principles. Voluntary Process Guidelines for Issuing Social Bonds. Paris.
22. KPMG. 2019. The Numbers That Are Changing the World. Revealing the Growing Appetite for Responsible Investing. Amstelveen, Netherlands.
23. LTS International.2018. Program Evaluation Final Report: Global Agriculture and Food Security Program (GAFSP). Edinburgh.
24. Millan A., B. Limketkai, and S. Guarnaschelli. 2019. Financing the Transformation of Food Systems under a Changing Climate. CCAFS Report. Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security.
25. Schmelzing, P. 2020. "Global Real Rates 1311-2018." Underground (blog) July 7. https://bankunderground.co.uk/2020/07/07/global-real-rates-1311-2018/
26. Von Braun, J., K. Afsana, L. Fresco, M. Hassan, and M. Torero. 2020. "Food Systems: Definition, Concept and Application for the UN Food Systems Summit." Unpublished draft paper for the Scientific Group of the UN Food Systems Summit.
27. Von Braun, J., B.B. Chichaibelu, M. Torero, D. Laborde Debucquet, and C. Smaller. 2020. Ending Hunger by 2030–Policy Actions and Costs. Policy Brief. Bonn: Center for Development Research (ZEF).
28. World Bank and IMF. 2005. The Poverty Reduction Strategy Initiative: Findings from 10 Country Case Studies of World Bank and IMF Support. Washington, DC: World Bank.
29. ZEF (Center for Development Research, University of Bonn) and FAO. 2020. Investment Costs and Policy Action Opportunities for Reaching a World without Hunger (SDG 2). Bonn and Rome.

Food and Agriculture Organization of the United Nations

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

TRADE AND SUSTAINABLE FOOD SYSTEMS

by Andrea Zimmermann and George Rapsomanikis

ABSTRACT

Trade is an integral part of our food systems. It connects people at all stages of agricultural and food value chains, linking farmers with consumers across the world. It also links nations to each other and thus scales up from the domestic to global perspective. By moving food from surplus to deficit regions, trade promotes food security, the diversity of foods available, and can affect preferences and diets. Trade impacts food prices and the allocation of resources and thus is inherent with economic growth and interacts with the environment. At the same time, trade can create both winners and losers, resulting in inequality, and can generate negative social and environmental outcomes. This brief provides an overview of the current debate around trade in food and agriculture and illustrates the role that trade can play within food systems in balancing different dimensions of sustainability. While trade openness is generally conducive to food security and promotes economic growth, formulating trade policies to achieve multiple targets, including environmental, nutritional and social objectives, requires careful analysis. Trade policies may not be the best and most efficient instruments to achieve multiple objectives and they should be framed by complementary policies targeting specific aspects of sustainability. For example, in addressing climate change, one of today's most press-

ABOUT THE AUTHORS

Andrea Zimmermann, Economist, Food and Agriculture Organization of the United Nations (FAO)

George Rapsomanikis, Senior Economist, Food and Agriculture Organization of the United Nations (FAO)

ing challenges, a combination of food trade and domestic policy instruments can sharpen the adaptation and mitigation roles of trade and significantly contribute in providing incentives to promote climate-smart technologies. In order to effectively design such policies, a better understanding of both the complex linkages between trade and sustainability outcomes and the simultaneous impacts of policy approaches on all parts of the food system will be necessary.

1. INTRODUCTION

Trade is an integral part of our food systems. It connects people at all stages of agricultural and food value chains, promotes food security, is inherent with economic growth, and interacts with society and environment. Since 1995, agricultural and food trade has more than doubled in value, quantity, calories, and land used for export (FAO, 2020b; Qiang et al., 2020; Traverso and Schiavo, 2020). Today, about one-third of agricultural and food exports in the world are traded within global value chains that encompass at least three countries (Figure 1; FAO, 2020b).

Agricultural and food trade links the food systems of countries and plays a crucial role in providing consumers worldwide with sufficient, safe and nutritious food, while generating income and employment for farmers, workers and traders in agriculture and food industry.

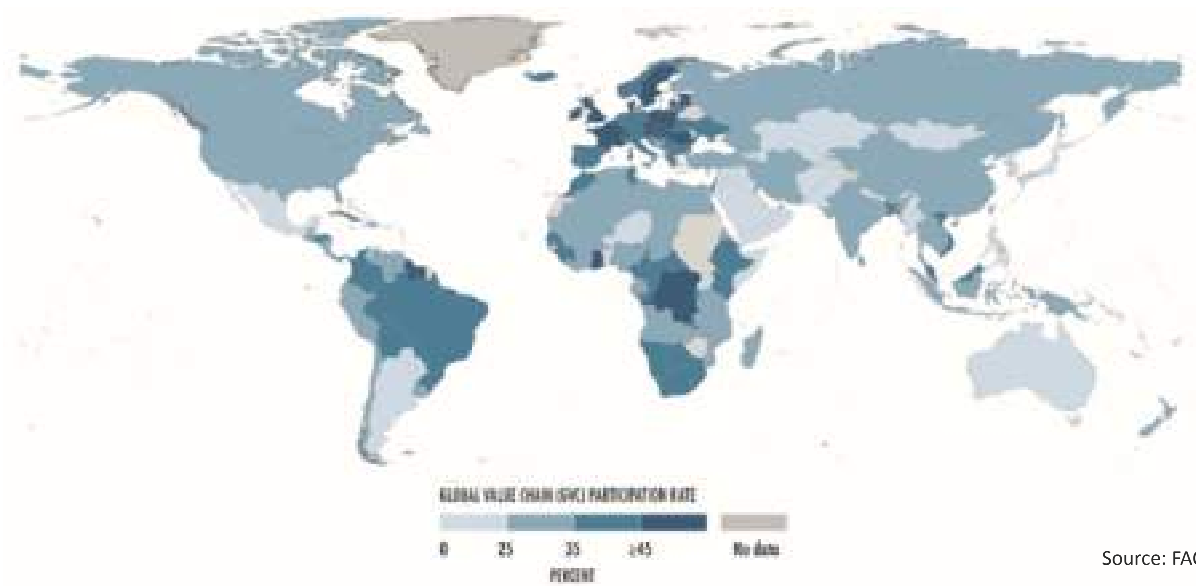
Trade is closely related to economic development. Developed countries make up more than 60 percent of agricultural and food trade. Emerging economies, such as Brazil and China, have been increasing their market shares since the early 2000s and play an increasingly important role in global agricultural and food markets (FAO, 2018a, 2020b).

At the same time, and as the interdependence between nations strengthens, the role of trade in society and income distribution becomes more important (FAO, 2020b). This, together with the emergence of new players in global markets, has induced lively debates on what economic, environmental and social outcomes trade and global markets generate. These debates have been intensified and broadened through significant concerns about inequality, growing environmental consciousness, changing lifestyles and diets that have been attributed to globalization and the related concerns about health risks associated with increasing shares of overweight and obese people (FAO, 2016, 2018b, 2020b).

The COVID-19 pandemic has fueled fears about the functioning of global agricultural and food trade and the discussion about reshoring tendencies in manufactures and services and shortening global value chains has also reached food and agriculture.

However, agricultural production strongly depends on specific natural resource endowments and environmental conditions, such as soil characteristics, altitude, water availability and climate. These are distributed unevenly across the world and, together with differences in technology, shape trade flows. This distinguishes agricultural and food trade from trade in manufactures and services. In fact, since the Neolithic period, agricultural and food trade has evolved in line with the comparative advantage derived from these immutable characteristics (see for example, Smith et al., 2015).

Figure 1 Participation in global value chains in food and agriculture.



Source: FAO (2020b).

At the same time, the demand for food is increasing fastest in regions where population and income growth are strongest, but which may not always be the most productive. These developments may reinforce the role of trade in ensuring food security and providing nutritious and healthy diets for all.

This brief highlights the role of agricultural and food trade in moving food globally from surplus to deficit regions, thus ensuring food security and serving a fundamental food systems function. It further addresses the interlinkages between trade and economic development, the environment and societal shifts in food consumption. Ultimately, the brief illustrates the role that trade can play in balancing different aspects of sustainability from a global perspective and points out the scope for further research and novel policy approaches.

2. TRADE, FOOD SECURITY AND NUTRITION

Trade in food and agriculture can help balance food supply and demand globally by moving food from surplus to deficit areas. Higher food imports can increase the availability of calories and nutrients in a country. Through increased food supply, food prices would fall, thus improving access for net consumers. At the same time, decreasing food prices induced by import competition can also affect incomes and livelihoods of domestic farmers and food processors who are net producers. However, for a country, increased trade openness may also allow for better access to other countries' markets and promote exports of agricultural products to these markets, thereby creating and expanding employment opportunities and raising workers' incomes (Dithmer and Abdulai, 2017; FAO, 2016).

By moving food from surplus to deficit areas at times of shortages, which might, for example, be caused by natural disasters or seasonal growing patterns, trade can also contribute to more stable food supplies and prices and thus to the stability dimension of food security. The exchange of foods that are produced under specific climate, soil and other natural conditions, can contribute to the diversity of diets (Remans et al., 2014) and improved food utilization (FAO, 2016, 2018b).

Although the theoretical pathways of how trade can affect food security and nutrition are well established, the linkages between agricultural and food trade and food security and nutrition are complex and some of the impacts can offset each other. This makes the identification of the effects in empirical assessments difficult. In fact, there has so far been only little empirical evidence on these relationships (FAO, 2018b; Mary, 2019).

A relatively new strand of literature contrasts trade openness with direct nutritional outcomes such as undernourishment. At global level, it was shown that agricultural trade openness has, on average, a positive net impact on food security measured as dietary energy supply adequacy. It also increased dietary diversity measured as the share of calories from non-staple foods and protein consumption (Dithmer and Abdulai, 2017). However, the exact mechanisms and impacts can vary by context and stage of development (FAO, 2016). For example, in a sample of 52 developing countries, food trade openness was associated with an increase in the prevalence of undernourishment. In fact, it was found that food supply increased as a result of increased trade openness, but, in net food-importing countries, the negative effect on agricultural producers and the food sector caused by import competition prevailed. This result could point to efficiency constraints in net importing countries with large agricultural sectors (Mary, 2019).

Besides trade openness, the ease by which trade takes place also matters. For example, poor trade facilitation with high bureaucratic requirements and lengthy export and import times can negatively affect various dimensions of food security, as shown in a study of 45 African countries observed between 2006 and 2015 (Bonuedi, Kamasa and Opoku, 2020).

Among the most-researched relations within the area of agricultural trade and food security are the linkages between trade and price volatility. Price volatility, which is described by episodes of large and unexpected price changes, can intensify and contribute to risks to food security (Kalkuhl, von Braun and Torero, 2016). In particular, the food price crisis of 2007/08 has triggered a plethora of studies on its causes. While a whole set of macroeconomic and sector-specific drivers for the price surges has been identified (Tadesse et al., 2014), it is now well established that trade restrictions that were imposed by many countries in response to rising food prices exacerbated food price volatility.

Trade-restricting measures, such as high import tariffs and export bans, reduce the volume traded in international markets and thus constrain the exchange mechanism between surplus and deficit areas. This makes markets more vulnerable to shocks and increases price volatility at times of crisis (Anderson, 2012). To insulate from sudden food price surges, countries tend to impose new or heighten existing export restrictions and/or lower import barriers so that the domestic price would rise less than the world market price (Rapsomanikis, 2011), with the effect that world markets become even thinner, market uncertainty increases and international food prices become more volatile (Anderson and Nelgen, 2012; Anderson, Rausser and Swinnen, 2013; Martin and Anderson, 2012).

Export restrictions, especially when applied by major exporters, can significantly harm their trading partners, in particular, net food-importing developing countries. For example, export restrictions implemented by various countries between 2006 and 2011, increased international price volatility for wheat and rice. In fact, the contribution of export restrictions to price volatility appeared to be in the same order of magnitude as that from key macroeconomic variables (Rude and An, 2015).

At the same time, export restrictions affect also domestic markets (FAO, 2016). For example, export restrictions on wheat applied by the major wheat exporters during the 2007/08 food price crisis not only harmed their trading partners but also reduced prices for domestic producers and increased domestic market instability. The negative market effects discouraged private investors and prevented the countries which imposed the export restrictions from achieving their production potential (Götz, Glauben and Brümmer, 2013).

Diet diversity is important for an adequate provision of nutrients and human health. As natural conditions do not allow producing all foods everywhere, trade is an important means to help diversify diets. A number of studies investigate the relationship between trade and dietary diversity.

Since the beginning of the 1960s, trade in crops has expanded and diversified. This process has been identified as the main driver of globally diversifying supply of vegetable products (Aguiar et al., 2020). In fact, the diversity of foods produced is a strong predictor of food supply diversity only in low-income countries, which are less integrated in international trade. In middle- and high-income countries, food supply diversity was shown to be independent of production diversity and other factors, including international trade, contributed more to a country's supply diversity (Remans et al., 2014).

Although lower-income countries are often not well integrated in global markets, a study found that they still tend to improve their nutrient supply through trade in particular the supply of energy, protein, zinc, calcium, vitamin B12 and vitamin A (Wood et al., 2018). However, in another study it was found that while trade distributes substantial volumes of nutrients, its role in bridging the nutrient adequacy gap[1] was only marginal in low- and lower-middle income countries. International trade helped close the nutrient gap in most high- and upper-middle-income countries, even where domestic production ensured only a very low nutrient adequacy (Geyik et al., 2021).

Taken together, the evidence shows that trade is indispensable to ensure food security in all its dimensions. Without trade, the availability and accessibility of foods and nutrients would be more unevenly distributed, any form of domestic production disruptions would cause serious concern for food security, and diets would be less diverse.

However, increased competition through rising imports may be challenging for farmers in developing countries that are characterized by low efficiency and productivity constraints associated with poor physical infrastructure, weak institutions and low skills.

3. TRADE, GROWTH AND INEQUALITY

The global trade regime – as it is reflected by the WTO rules and a multitude of trade agreements – has contributed to increasing trade significantly since the last decades of the 20th century. Population growth and urbanization, rising incomes and improvements in transport and communication technology have colluded with lower policy-induced trade barriers to fuel trade (FAO, 2020b).

Most economists would agree that openness to international trade promotes economic growth (Irwin, 2019). Trade results in efficiency gains as resources are allocated in line with comparative advantage, which is shaped by differences in technology and relative factor endowments. In agriculture, where differences in land and water endowments and climate are significant across countries, gains from openness and market integration can be large (Martin, 2018). These gains can add to the rate of growth of the economy but are difficult to estimate.

Isolating the impacts of trade openness, whether this comes from a reduction in trade costs or trade policy

1 The nutrient adequacy gap describes the difference between nutrient requirements and actual availability referring to six essential nutrients (protein, iron, zinc, vitamin A, vitamin B12 and folate) (Geyik et al., 2021).

reforms is challenging, given the myriad of factors that affect economic growth. In addition, focusing the analysis on single sectors, such as food and agriculture, can be complex. Using structural models to test counterfactual scenarios is the analysts' preferred method to untangle the role of trade and trade policy in economic growth. For example, a study looking at the effect of market integration across US counties between 1880 and 1997 suggests that such gains are substantial as agricultural production is allocated according to comparative advantage (Costinot and Donaldson, 2016).

In addition to the effect of efficiency gains, trade facilitates technology and knowledge spillovers across countries which promotes growth by improving the production process, increasing product quality and resulting in new products (Grossman and Helpman, 1991). Indeed, since 1995, the growth in food and agricultural trade has taken place together with increases in agricultural productivity per capita, particularly in emerging and developing economies (FAO, 2018a).

This conventional wisdom on the effects of trade openness on growth and productivity is being questioned by many practitioners. Gains from trade are asymmetrically distributed. Trade openness affects the prices of goods and those of production factors, including labor, and thus can result in winners and losers. In agriculture, a major concern relates to the ability of smallholder farmers from developing countries to compete effectively in open markets.

A handful of studies focus on the impact of trade openness on agricultural productivity, with the underlying hypothesis being that trade facilitates the diffusion of technology and knowledge spillovers. Focusing on how agricultural productivity in 44 countries – both developed and developing – converges at higher levels, a study finds that openness to trade increases labor productivity growth rates in agriculture within an analytical framework that also takes into account the costs of technology diffusion and adaptation (Gutierrez, 2002).

Additional evidence suggests that trade openness can have a short-run negative impact on agriculture's efficiency (Hart, Miljkovic and Shaik, 2015). However, in the long run, it is found to increase efficiency in agriculture, reflecting the ability of the sector to adapt to global markets and increased competition through technology adoption, but also through the exit of inefficient farms from the sector. In Chile – a country that liberalized trade in the 1990s after a period of import-substitution policies – an analysis of 70,000 farms suggests that trade openness is positively related to farm yields (Fleming and Abler, 2013).

Downstream, a study of more than 20,000 food firms in Italy and France suggests that import penetration in both final food products and intermediate inputs systematically contributes to firm-level productivity growth (Olper, Curzi and Raimondi, 2017). Participation in agricultural and food global value chains, either through imports of inputs or exports of intermediate products, is also found to promote agricultural labor productivity (FAO, 2020b; Montalbano and Nenci, 2020). The main mechanism for this lies on how value chains unbundle the production process, allowing farms and firms to leverage their comparative advantage in global markets and facilitating the transmission of improved technology, leading to better farm practices and improved labor productivity.

These linkages between trade openness and technology are unwrapped by a micro-level data study of the impact of trade in agricultural inputs on the productivity of 1.1 million fields across 65 countries. Since the 1980s, trade openness in agricultural inputs was found to result in significant shifts from traditional farm technologies to modern ones, thus having distributional implications for productivity and welfare across the world (Farrokhi and Pellegrina, 2020).

In addition to the efficiency gains from better resource allocation in agriculture and the dynamic effects on agricultural productivity through the transmission of technology and knowledge, trade openness in food and agriculture can generate significant effects on the broader economy by facilitating structural transformation. Trade in food, especially imports, can help meet domestic food requirements and allows labor to be allocated to non-agricultural sectors, thus promoting economic growth and development (Tombe, 2015). Analyzing the process of structural transformation in the UK in the 19th century and, more recently, in South Korea, a study finds that agricultural imports played a crucial role in the transformation process of both economies (Teignier, 2018).

Trade openness, either by intensifying competition or through fueling the structural transformation process, can promote growth but can also affect income distribution and inequality. A recent analysis of the impacts of eliminating tariffs on agricultural products across low- and middle-income countries pointed to increases in both income and inequality (Artuc, Porto and Rijkers, 2019). The results suggest that, on average, liberalizing agricultural trade would increase household incomes. At the same time, eliminating import tariffs was found to have highly heterogeneous impacts across countries, and within countries across households. In most countries, the top 20 percent of the richest households would gain more from liberalization than the bottom 20 percent, thus exacerbating inequality.

In the context of food systems, trade openness highlights the trade-offs between promoting economic efficiency and generating positive social outcomes. Integrating smallholder farmers in global markets is challenging. Policies that promote trade openness often tend to underplay market failures and the need for complementary actions to address inequality are necessary. Inclusive business models, such as contract farming, can address the constraints farmers in developing countries face in entering markets and global value chains (FAO, 2020b). However, a range of public policies and investments, such as carefully designed input subsidies targeted to smallholder farmers, skills upgrade and education, removing labor market rigidities, as well as improvements in infrastructure and regulation, can complement the market mechanism and promote a fair structural transformation.

4. TRADE, ENVIRONMENT AND CLIMATE CHANGE

Agriculture builds one complex with the environment. Natural resources and climate are inputs to agricultural production and a part of the human impact on the environment is transmitted through this production process.

While expected changes in climatic and environmental conditions over the coming decades will affect food security and nutrition, short-term shocks, such as natural hazards, pests, diseases and extreme weather events, already lead to harvest losses and supply chain disruptions. In regions with limited access to international markets and where food production and consumption are tightly coupled, these shocks can more readily translate into local shortages of (specific) foods (Davis, Downs and Gephart, 2021).

At the same time, changes in trade flows are associated with changes in agricultural production, which can influence greenhouse gas (GHG) emissions, land and water use and biodiversity through positive and negative externalities. Because of the spatial heterogeneity of resource availability, resource productivity, and farming practices, the environmental impact of producing food is localized and highly dependent on its origin. Depending on whether the environmental impact of agricultural production is greater or smaller in the exporting region than in alternative production sites, agricultural and food trade can therefore either increase or reduce the aggregate impact of agriculture on the environment globally (Dalin and Rodríguez-Iturbe, 2016).

By contributing to a better allocation of production across countries, trade can improve the utilization of natural resources in agriculture at the global level, which, in aggregate, can be beneficial to the environment (Roux et al., 2021). Without trade, some countries would have to produce a wider range and larger quantities of foods, even if their natural endowment was not compatible with such an expansion, placing an additional pressure on their ecosystems.

For example, increased agricultural production in net food-importing countries in the Middle East and North Africa would likely be at the expense of further water depletion in an already water scarce region (Biewald et al., 2014).

However, greater import demand and demand for specific products in some regions of the world can also lead to the depletion of natural resources and/or increased pollution in exporting countries.

In particular, if comparative advantage is derived from differences in environmental regulation, production might shift to countries with relatively laxer regulation, leading to worse environmental outcomes on the aggregate (Grossman and Krueger, 1991).

Moreover, trade can induce technological change, including through transfer of technology and best practices between trading partners, and leading to increased productivity and more efficient resource use (Grossman and Krueger, 1991). For example, greater agricultural output per hectare may release some agricultural land from production (land sparing) which thus becomes available for natural habitats and species, contributing to wildlife biodiversity (Phalan et al., 2011).

In order to analyze the impact of trade on resource use and pollution, a growing literature expresses trade flows in terms of the resource inputs and emission content they carry (virtual resource trade, carbon/land/water footprint). In fact, while trade was found not to be a major topic in ecosystem research based on a survey of ecological journals published in 2017 (Pace and Gephart, 2017), the literature on interactions between trade and the environment has been rapidly expanding. The analysis of impacts of agricultural trade on the environment mainly centers on climate change and the use of water and land, also covering deforestation (Balogh and Jámbor, 2020).

4.1. Climate change

Agricultural trade can play a role in both adjusting to the effects of climate change (adaptation) and reducing GHG emissions from agriculture (mitigation).

Trade as adaptation mechanism

Climate change may lead to significant trade disruptions in the short term (through extreme weather events) and long-term changes in trade patterns through altering countries' comparative advantage. Trade could help countries adapt to short-term supply disruptions and long-term changes in comparative advantage triggered by climate change (FAO, 2018a).

As climate change is expected to have an uneven effect across regions, trade can be an important avenue in ensuring food security. In studies on climate change impacts on agriculture in the time period 2050 to 2100, low-latitude regions such as the Near East, North Africa, sub-Saharan Africa and South Asia are often projected to be adversely affected, whereas high-latitude regions such as North America, parts of South America (e.g. Chile), Central Asia and Eastern Europe are expected to experience largely positive impacts on agricultural production (FAO, 2018a; Reilly, 1995; Wheeler and von Braun, 2013).

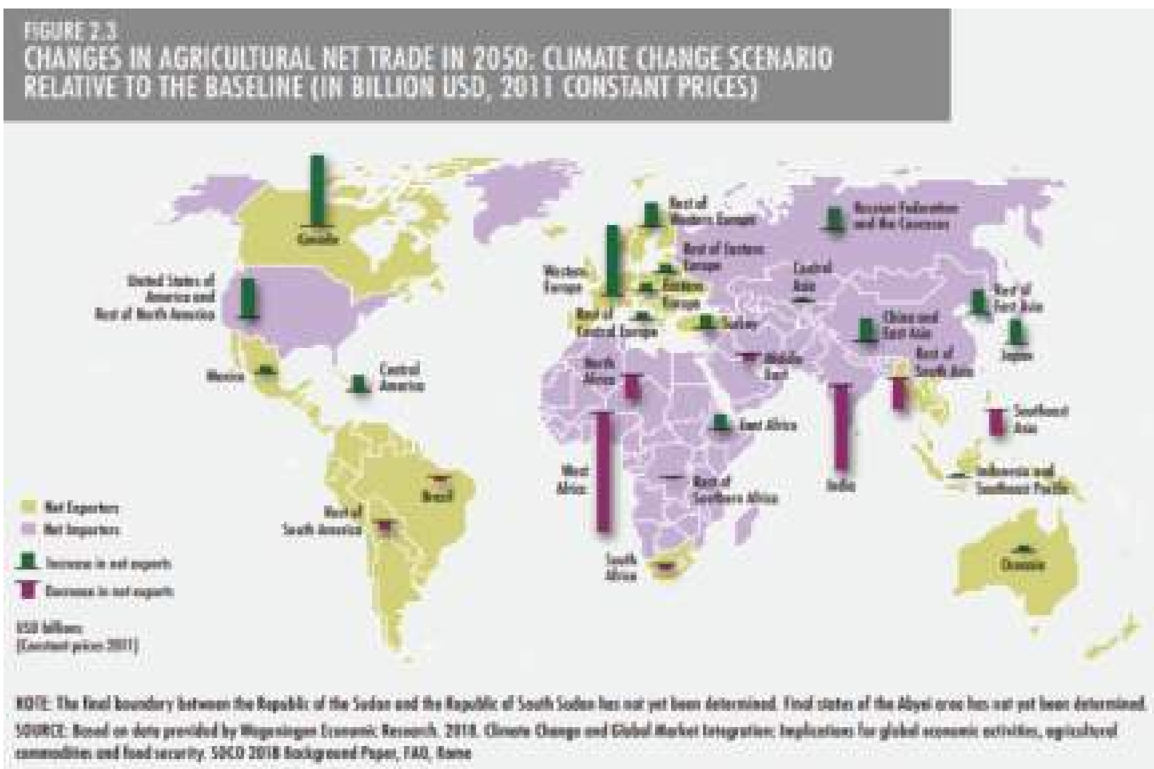
Under deteriorating conditions for agricultural production due to climate change, food imports by relatively more adversely affected (often developing) countries will have to come from those countries (often developed) that are relatively less adversely affected.

In fact, most studies integrating biophysical and economic models project a stronger role for trade as a result of climate change at the global level (Ahammad et al., 2015; Baldos and Hertel, 2015; FAO, 2018a; Havlík et al., 2015; Janssens et al., 2020; von Lampe et al., 2014, 2014; Nelson et al., 2014; OECD, 2015; Schmidhuber and Tubiello, 2007; Figure 2).

However, the adaptive role of trade in ensuring food security, could be constrained by trade restrictions and structural barriers to adjustment.

While a substantial part in mitigating adverse effects from climate change in agriculture would come from endogenous production adjustments, such as shifts in production patterns, in line with evolving comparative advantage (Costinot, Donaldson and Smith, 2016; Gouel and Laborde, 2021), freer trade could indeed offset part of the welfare losses from climate change (Costinot, Donaldson and Smith, 2016; Gouel and Laborde, 2021; Stevanović et al., 2016; Wiebe et al., 2015). Open mar-

Figure 2 Projected changes in agricultural net trade in 2050: climate change scenario relative to a no-climate change baseline (in billion USD, 2011 constant prices).



Source: Cui et al. (2018); FAO (2018a).

kets could also contribute towards food security, especially in adversely affected regions that are already characterized by a high prevalence of undernourishment (Baldos and Hertel, 2015; Janssens et al., 2020).

The aggregate patterns of climate change effects at global and regional level can mask differences in the distribution of gains and losses within countries and regions. Through the balancing mechanism of international trade, agricultural and food prices in adversely affected regions would be relatively lower under free trade compared to a scenario in which trade is restricted. This would benefit net food consumers, while agricultural producers could lose. At the same time, farmers in less affected or even benefiting regions could gain from relatively higher prices under free trade, while consumers would face welfare losses (Stevanović et al., 2016).

As labor productivity in agriculture would be more affected by higher average temperatures than in other sectors of the economy, affected countries could adapt to climate change by importing food and shifting labor towards non-agricultural sectors. However, under limited market integration, subsistence food requirements in many developing countries could drive specialization even towards, rather than away from, agriculture, thus exacerbating losses from climate change (Nath, 2020).

Trade in climate change mitigation

Foresight analyses suggest that between 2012 and 2050 agricultural production will have to increase by 50 percent to provide food for a growing and progressively more wealthy population (FAO, 2018c). Such increases in production could also result in increases in global GHG emissions unless food systems become 'emissions efficient' and produce lower emissions per unit of output. As trade will expand to contribute to climate change adaptation, increased transport will also add to the emissions (FAO, 2018a; Pendrill et al., 2019; Schmitz et al., 2012, 2015). The ultimate impact on global emissions depends on whether imports are sourced from systems that operate at lower emissions efficiency or from ones that operate at higher emissions efficiency (Table 1).

Several policy incentives can help improve emissions efficiency and lower GHG emissions. For example, taxing GHG emissions is a way to 'internalize' their full cost to the society and can provide incentives to farmers to adopt technologies and practices that promote climate change mitigation (FAO, 2018a).

However, mitigation policies implemented through a uniform global carbon price would curb emissions but also reduce agricultural production, raise agricultural commodity prices, and impact food security. Underlining the trade-offs between food security, nutrition and emission reduction targets, especially for developing countries, the most significant reduction in consumption as a result of global carbon taxes has been projected for livestock products in sub-Saharan Africa (FAO, 2018a; Havlík et al., 2015).

If instead carbon taxes were imposed unilaterally, countries that try to internalize the cost of GHGs may inadvertently confer a competitive advantage on others that do not impose a similar measure, potentially leading to emissions leakage and misallocation. This would imply the risk of increasing production and exports from countries without mitigation policies resulting in emissions leakage. In this case, the impact of this leakage on global emissions may be positive (emissions reallocation) or negative (emissions misallocation) depending on the relative emissions efficiency of domestic production vis-à-vis imports (Table 1). Specific trade policies can contribute towards addressing the trade-off between food security and emission reduction targets. To even out disparities between domestic and international levels of carbon taxes, border measures, such as border tax adjustments based on food products' carbon footprints, could be implemented (FAO, 2018a).

Table 1 Impacts of emissions leakage through trade

Relative emissions efficiency (between imports that displace domestic products)	Impact on global emissions	Result of emissions leakage
Imports are produced in systems with **lower emissions efficiency** (higher emissions per unit of output)	**Increase** in global emissions	**Emissions misallocation**
Imports are produced in systems with **higher emissions efficiency** (lower emissions per unit of output)	**Decrease** in global emissions	**Emissions reallocation**

Source: FAO (2018a).

Instead of, or in addition to taxing GHG emissions, labeling of final products with respect to GHGs emitted during their production can be a way of shaping consumer preferences towards less-emitting production practices.

Common to all of these policies is that they would require an accurate and complete assessment of the costs incurred to the society by the GHGs emitted during agricultural and food production, or, as usually done in practice, a reliable estimate of the direct emissions involved in the production process of different foods, namely the carbon footprint.

However, already the consistent accounting of GHG emissions in agriculture implies several challenges, including methodological issues and excessive data requirements. Carbon footprints need to be quantified encompassing the emissions generated in the production and supply of inputs used by farmers, direct and indirect emissions generated in agricultural production processes, and subsequent emissions associated with transportation, processing, storage, and delivery of products to consumers (FAO, 2018a; Rosenzweig et al., 2020). In particular, agricultural production involves many different sources of emissions that need to be covered. Moreover, these sources of emissions are often diffuse, difficult to monitor and can vary by location (Escobar et al., 2020). For example, fertilizer use is a major source of nitrous oxide emissions, but measuring the emissions from a given area of land is complicated, since it depends on factors other than the amount of fertilizer applied, many of which are site-specific (e.g. management practices, soil types, and weather) (FAO, 2018a).

In addition to overcoming technical challenges in determining carbon footprints in agriculture and possible trade-offs with food security through certain mitigation policies, the carbon accounting mechanisms would also need to be agreed upon internationally to avoid any trade disputes (FAO, 2018a).

Alternative policy approaches to reduce GHG emissions from agriculture center on domestic measures to incentivize climate-smart agricultural practices. These can be indirectly related to trade by altering traded volumes and market signals (FAO, 2018a).

4.2. Land, water, biodiversity

Besides GHG emissions, agricultural production can affect natural resources, such as land and water, and biodiversity. Through trade, these external effects can occur in countries far away from the final point of consumption. In the case of water, these externalities are mainly positive (Dalin and Rodríguez-Iturbe, 2016). By importing products and services from countries with abundant water resources, water-deficient countries can alleviate the pressure on their own water supply (Deng et al., 2021; Pastor et al., 2019).

With increasing agricultural trade, the total land use embodied in agricultural trade also more than doubled (almost tripled) between 1986 and 2016. As in the case of water, countries with absolute or relative abundance of land, such as the United States, Brazil and Argentina, are net exporters of 'virtual' agricultural land. Countries with relatively less land per capita, such as Japan, the Netherlands and mainland China, are among the net importers of 'virtual' land. Countries with relatively little arable land but high yields, such as European and some Asian countries, tend to export high-value agricultural products, such as fruits, vegetables and animal-based foods (Qiang et al., 2020).

However, due to trade-offs with other resource uses, trade may not always allocate production to the regions with the most efficient land use (Roux et al., 2021). For example, a globally optimal allocation of water use might imply an expansion of land use into natural areas and forests (Pastor et al., 2019).

By specializing agricultural production away from certain products that are increasingly imported, land use changes can occur also in importing countries. For example, increased nitrogen pollution was observed in countries that shifted from domestic soybean production to increased soybean imports. In these cases, farmland that was originally used for cultivating soybeans, which can fix nitrogen and require significantly less fertilizer, was converted to grow crops such as wheat, corn, rice, and vegetables, which are more prone to overfertilization (Sun et al., 2018).

Land use affects also biodiversity. On the one hand, some farming systems can be beneficial to biodiversity and many ecosystems depend directly on agricultural land use (Henle et al., 2008; Tscharntke et al., 2012). On the other hand, the conversion of natural habitats to farmland can lead to displacement or eradication of wildlife (Rockström et al., 2009), and biodiversity in existing agricultural systems can be affected by an overuse of agrochemicals and certain forms of land management.

By distinguishing between biodiversity loss from agricultural land used for exports and domestic consumption, increasing import demand from developed countries is sometimes found to be the main driver for biodiversity loss in exporting countries (Chaudhary and Brooks, 2019; Chaudhary and Kastner, 2016; Lenzen et al., 2012; Moran and Kanemoto, 2017). However, more systematic research covering multiple disciplines, various dimensions/indicators of biodiversity and counterfactuals is needed to provide comprehensive assessments of biodiversity footprints (de Chazal and Rounsevell, 2009; Marquardt et al., 2019; Ortiz et al., 2021).

Overall, the evidence on the effects of extreme weather events, natural hazards, pests and diseases on food systems is concentrated on the main staple crops (maize, rice and wheat) and relatively few types of shocks (Davis, Downs and Gephart, 2021). Similarly, the analysis of the impact of trade on the environment also tends to focus on aggregated trade or on trade in staple food crops. Only very recently have studies considered the impacts of a broader range of specific products, such as trade in cash crops (Sporchia, Taherzadeh and Caro, 2021).

Ensuring food security and satisfying dietary needs for a growing number of people, especially in already food-deficit regions, may not be possible without exploiting the relative comparative advantage in other regions of the world.

5. GLOBALIZATION OF FOOD: TRADE, SOCIAL AND HEALTH IMPACTS

Improvements in productivity and the expansion of international trade have increased the availability of food, reduced food prices and contributed to overall declining rates of undernutrition in the world. At the same time, together with higher incomes and a more sedentary lifestyle, trade is also associated with increasing rates of overweight and obesity worldwide (FAO, 2018b, 2020b).

The liberalization of trade and investment have sometimes been identified as being among the key mechanisms through which globalization impacts health (Cowling, Thow and Pollack Porter, 2018; Mary and Stoler, 2021). Overall, the empirical literature appears to point to a broad association between trade liberalization, improved dietary quality and reduced undernutrition (Cuevas García-Dorado et al., 2019).

However, subject to context and method of analysis, the body of empirical work investigating the relationship between globalization, trade in food and agriculture and health outcomes finds mixed results (Cowling, Thow and Pollack Porter, 2018; Cuevas García-Dorado et al., 2019; Mary and Stoler, 2021).

Some studies explore the relationship between globalization indices and average body mass index (BMI: kg/m^2) in a country. In low-income countries, increasing mean BMIs can indicate a reduction in undernutrition, while high mean BMIs can also indicate a greater prevalence of overweight in a country.

Economic globalization, measured as an index of trade and foreign direct investment (FDI) flows and restrictions[2] was found to be positively related to increases in mean BMI (Vogli et al., 2014). The relationship between economic freedom[3] and BMI was found to be very weak overall. Only in the case of men living in developing countries was an increase in economic freedom associated with slightly higher BMIs (Lawson, Murphy and Williamson, 2016).

Several studies consider indicators different from BMI, such as the prevalence of obesity and/or overweight. The economic integration (or economic globalization; see above) between countries is often shown to have no or a decreasing effect on the prevalence of overweight (Costa-Font and Mas, 2016; Goryakin et al., 2015; de Soysa and de Soysa, 2018).

Globalization can also manifest in shifts in socio-cultural norms, which, in turn, affect consumer preferences, diets and nutritional outcomes. A closer social integration, measured as an index of personal international contacts, international information flows and cultural proximity (Dreher, 2006), is sometimes found to be positively associated with obesity (Costa-Font and Mas, 2016; Goryakin et al., 2015).

2 Several studies distinguish between the impact of economic, political and social globalization based on the KOF index (Dreher, 2006). According to this index, economic integration refers to actual trade and FDI flows and restrictions. Political integration is composed of a country's international engagement with other countries and international organizations and social integration measures personal international contacts, international information flows and cultural proximity.

3 Economic freedom was measured with the Economic Freedom of the World index. The index assesses the degree to which policies and institutions of countries are supportive of economic freedom. It measures economic freedom in five broad areas: size of government; legal systems and property rights; sound money; freedom to trade internationally; and regulation (Gwartney, Lawson and Hall, 2013).

However, socio-cultural aspects of globalization and access to information and communication technology were found to reduce the share of overweight and obese young people aged between 15 and 19, suggesting that increased international interconnectivity in this age group might help spread knowledge about healthier eating and lifestyle habits (Knutson and de Soysa, 2019).

Recent studies also explore the relationship between (general) trade openness and obesity rates. For example, an increase in trade openness was associated with increasing overweight and obesity rates in Brazil (Miljkovic et al., 2018) and at global level (An et al., 2019). This relationship appeared to be stronger in developing countries with high economic growth rates, while no relationship between trade openness and obesity prevalence was identified among high-income countries (An et al., 2019).

In a study on the effects of social globalization and trade openness on average BMI and different indicators of diet quality, increasing social globalization was associated with higher mean BMI, animal protein and sugar supply. These results seem to be driven by specific components of social globalization such as information flows through television and internet. Trade openness did not reveal any effect on dietary outcomes or health (Oberlander, Disdier and Etilé, 2017).

A critical review of methodological approaches used in quantitative analyses of the impacts of global trade and investment on non-communicable diseases and risk factors, encourages future studies, inter alia, to clearly define the exposure of interest and, in particular, not to conflate trade and investment; explore the mechanisms of broader relationships that might steer the results; adjust for reverse causality; increase the use of individual-level data; and, consider sector-specific rather than economy-wide trade and investment indicators (Cowling, Thow and Pollack Porter, 2018).

Empirical evidence on the interlinkages between trade in food and agriculture and nutritional outcomes remains scarce and, so far, only a few studies have explored these linkages more systematically (FAO, 2020b). Agricultural and food trade constitutes an important means to ensure diet diversity. However, as trade improves the availability and accessibility of both foods necessary for a healthy diet and foods high in fat, sugar, salt and calories, the effects on nutritional outcomes can be mixed (FAO, 2018b, 2020b; Krivonos and Kuhn, 2019).

In fact, trade has helped overcome the constraints the uneven distribution of natural resource endowments poses on the supply of foods and nutrients across countries. A study suggests that trade resulted in food and nutrients being more equally distributed in 2010 than in 1970 (Bell, Lividini and Masters, 2021).

Agricultural trade openness has also been associated with increasing overweight and obesity prevalence in developing countries (Mary and Stoler, 2021); rising imports of sugar and processed foods were found to be correlated with slightly higher average BMIs (Lin, Teymourian and Tursini, 2018); and the exposure to food imports from the United States of America was found to explain part of the rise in obesity prevalence among Mexican women between 1988 and 2012 (Giuntella, Rieger and Rotunno, 2020).

6. THE TRADE POLICY ENVIRONMENT

International trade negotiations in the General Agreement on Tariffs and Trade (GATT), and subsequently under the WTO, have contributed to opening global markets and barriers on agricultural and food trade have declined since the Uruguay Round of the GATT and the WTO Agreement on Agriculture in 1995.

Since the beginning of the 1990s, the number of regional trade agreements that have been notified to the WTO has also risen, from fewer than five in 1990 to 339 being in force in 2021. European countries are currently the main partners in regional trade agreements, followed by countries in East Asia (WTO, 2021).

Considerable attention has been paid to prospects for development from the African Continental Free Trade Area (AfCFTA). The AfCFTA covers 54 of the 55 African Union (AU) Member States and entered into force in May 2019, with trade commencing in January 2021 (FAO and AUC, 2021). The AfCFTA is expected to significantly increase intra-African trade of agricultural and food products, with estimates ranging between 20 and 30 percent increase in 2040 compared to a scenario without the AfCFTA (United Nations Economic Commission for Africa, 2018; United Nations Economic Commission for Africa and TradeMark East Africa, 2020).

In contrast to multilateral trade agreements, regional trade agreements grant concessions only to a few trade partners, discriminating against others. The proliferation of regional trade agreements is sometimes seen as "building blocks" towards multilateral trade liberalization, but could also hinder further integration

(Bhagwati, 1991, 1993). This discussion is of particular relevance in the agricultural sector (Sheldon, Chow and McGuire, 2018), for which also the depth of many regional trade agreements and thus their actual potential to impact members' trade has been called into question (Grant, 2013).

More recently, the use of environmental provisions in trade agreements has increased considerably, a trend that is particularly strong in agreements between industrialized and developing countries (Morin, Dür and Lechner, 2018). Moreover, the consideration of nutritional objectives in trade agreements has also emerged (Thow and Nisbett, 2019), with the discussion in multilateral fora focusing on issues related to nutrition labeling (Thow et al., 2018).

While the strong focus on environmental and nutrition aspects in trade policy is relatively new, non-tariff measures, especially food safety standards and their international harmonization, continue to be a major point of discussion in agricultural trade (FAO, 2020a; Santeramo and Lamonaca, 2019; Wieck, 2018).

These discussions on environmental provisions and nutritional issues in the context of trade trace the multiple trade-offs between economic, environmental and social objectives within food systems. They also highlight that, in general, the market mechanism cannot guarantee the provision of a range of social and environmental benefits that are central to sustainable development. Food and agricultural trade may result in negative environmental outcomes or may fail to address social objectives, such as reducing inequality.

In food and agriculture, trade policy measures address a broad array of mainly economic objectives. For example, tariffs are commonly used to protect local producers from international competition and can contribute towards maintaining a level of farm income that keeps pace with income in other economic sectors. Tariffs are also used to reduce import dependence and promote self-sufficiency in staple foods. Export restrictions can lower the domestic price of food and contribute towards food security in the short term. Both tariffs and export taxes provide an important source of government revenue. Other measures, such as non-tariff barriers, aim at improving the safety and quality of food. All of these policy instruments should address their objectives as sustainably as possible but can also entail positive or negative external effects to society and the environment.

Within a food systems approach to trade, policy formulation based on tariffs or export restrictions to address environmental and social objectives, such as the preservation of biodiversity, better nutrition or equity, might be very costly and not sufficient to achieve all sustainability targets.

Externalities or non-economic objectives, such as those considered in this brief, are best addressed by policies that act directly on the relevant margin, as for example, by domestic policy instruments, such as taxes and subsidies, rather than introducing trade distortions. Formulating policies at the margin implies a 'targeting principle' that allows ranking different policy instruments in line with their effectiveness in addressing externalities or non-economic objectives (Bhagwati and Ramaswami, 1963; Dixit, 1985; Rodrik, 1987). Trade policies may not be the best and most efficient way to address externalities and achieve environmental objectives. For example, a domestic carbon tax acts on the margin, providing incentives to farmers to reduce emissions and adopt climate-smart farming technologies.

In some cases, policy objectives can be independent of each other. For example, the prevalence of overweight and obesity can be addressed by taxes on the sugar or fat content of food or raising awareness on healthy diets, rather than trade policies. A basic principle of effective policy-making – the Tinbergen rule – indeed suggests that to achieve a number of independent policy targets at least the same number of independent policy instruments are required (Tinbergen, 1952).

Political economy considerations suggest that trade policies can also be endogenous in the sense that they have been created by pressure groups, such as producer organizations, exerting influence on the policy-making process. In this case, the 'targeting principle' may not apply. For this reason, it is important to understand the process by which policies are formulated and consider context-specific policy approaches instead of broad principles (Rodrik, 1987).

While open markets and free trade are conducive to global food security and promote economic growth, liberalization processes can create winners and losers and thus should be framed and supported by complementary policies that address market failures, externalities and system-inherent distortions. For example, addressing inequality can be achieved by redistributing gains from liberalization and facilitating mobility across sectors.

In order to effectively design such policies, a better understanding of their simultaneous impacts on all parts of the food system will be necessary. Evolving food systems research will require both strong disciplinary approaches and analytical tools integrating several dimensions and multi-level perspectives (van Ittersum et al., 2008). It will also require effective communication of "plurality and conditionality of complex, dynamic systems research" (Zurek et al., 2018) to non-expert audiences and policy-makers.

Key policy issues to be considered on the Food Systems Summit agenda:

Recognize the role of trade in promoting food security, economic growth and better natural resource use and management

Trade openness contributes towards global food security and better nutrition, a better allocation of food production, and a more efficient and sustainable use of natural resources across countries. For a country, participation in global markets and value chains facilitates the diffusion of technology and knowledge and leads to increased productivity and more efficient resource use. To allow trade to flow smoothly and fulfill these functions, unjustified trade distortions and barriers should be avoided. Enhancing market transparency through improved information, cutting red tape and simplifying trade procedures through digitalization can significantly facilitate trade.

Implement complementary policies to address the trade-offs between economic and social objectives in the context of open markets

Open markets lie at the heart of the development process. In developing countries, a range of public policies and investments can help farmers overcome constraints to market access and create an enabling environment for a prospering economy for all. These include skills upgrade and education, removal of labor market rigidities, and improvements in infrastructure, institutions and regulation. Social protection mechanisms and redistribution of economic gains of trade openness to vulnerable population groups can improve inclusion and reduce inequalities.

Strengthen the role of trade in climate change adaptation and mitigation

As climate change is expected to have an uneven effect across regions, trade openness can be an important avenue in ensuring food security in countries which are more adversely affected by global warming and extreme weather shocks. However, the mitigating role of trade is equally important. Internalizing the cost of climate change in the food price across countries can help trade reallocate agricultural production to regions where emissions per unit of output is lowest. This can address the dual challenge of meeting food demand growth in the future and reducing greenhouse gas emissions.

Maximize the gains from trade for all countries

Both regional agreements and multilateral mechanisms can support trade and economic growth. Nevertheless, as food surplus and deficit areas may be located in different world regions and specific products may be most efficiently produced in other parts of the world, gains from agricultural and food trade can be maximized through multilateral mechanisms. Multilateral mechanisms can also help guide an optimal policy mix in addressing trade-offs between economic, health and environmental objectives, such as the harmonization of food safety standards and the development of a common understanding on sustainability certification.

REFERENCES

1. Aguiar, S., Texeira, M., Garibaldi, L.A. & Jobbágy, E.G. 2020. Global changes in crop diversity: trade rather than production enriches supply. Global Food Security, 26: 100385.
2. Ahammad, H., Heyhoe, E., Nelson, G., Sands, R., Fujimori, S., Hasegawa, T., van der Mensbrugghe, D., Blanc, E., Havlík, P., Valin, H., Kyle, P., d'Croz, H., van Meijl, H., Schmitz, C., Lotze-Campen, H., von Lampe, M. & Tabeau, A. 2015. The role of international trade under a changing climate: insights from global economic modelling. In: A. Elbehri, ed. Climate change and food systems: global assessments and implications for food security and trade, pp. 293–312. Rome, FAO.
3. An, R., Guan, C., Liu, J., Chen, N. & Clarke, C. 2019. Trade openness and the obesity epidemic: a cross-national study of 175 countries during 1975–2016. Annals of Epidemiology, 37: 31–36.
4. Anderson, K. 2012. Government trade restrictions and international price volatility. Global Food Security, 1(2): 157–166.
5. Anderson, K. & Nelgen, S. 2012. Trade barrier volatility and agricultural price stabilization. World Development, 40(1): 36–48.
6. Anderson, K., Rausser, G. & Swinnen, J. 2013. Political economy of public policies: insights from distortions to agricultural and food markets. Journal of Economic Literature, 51(2): 423–477.
7. Artuc, E., Porto, G. & Rijkers, B. 2019. Household impacts of tariffs: data and results from agricultural trade protection. Policy Research Working Papers. The World Bank. 40 pp. (also available at https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-9045)
8. Baldos, U.L.C. & Hertel, T.W. 2015. The role of international trade in managing food security risks from climate change. Food Security, 7(2): 275–290.
9. Balogh, J.M. & Jámbor, A. 2020. The environmental impacts of agricultural trade: a systematic literature review. Sustainability, 12(3): 1152.
10. Bell, W., Lividini, K. & Masters, W.A. 2021. Global dietary convergence from 1970 to 2010 altered inequality in agriculture, nutrition and health. Nature Food, 2(3): 156–165.
11. Bhagwati, J. 1991. The world trading system at risk. Princeton, Princeton University Press. 156 pp.
12. Bhagwati, J. 1993. Regionalism and multilateralism: an overview. In: J. de Melo & A. Panagariya, eds. New dimensions in regional integration, pp. 22–51. Cambridge University Press.
13. Bhagwati, J. & Ramaswami, V.K. 1963. Domestic distortions, tariffs and the theory of optimum subsidy. Journal of Political Economy, 71(1): 44–50.
14. Biewald, A., Rolinski, S., Lotze-Campen, H., Schmitz, C. & Dietrich, J.P. 2014. Valuing the impact of trade on local blue water. Ecological Economics, 101: 43–53.
15. Bonuedi, I., Kamasa, K. & Opoku, E.E.O. 2020. Enabling trade across borders and food security in Africa. Food Security, 12(5): 1121–1140.
16. Chaudhary, A. & Brooks, T.M. 2019. National consumption and global trade impacts on biodiversity. World Development, 121: 178–187.
17. Chaudhary, A. & Kastner, T. 2016. Land use biodiversity impacts embodied in international food trade. Global Environmental Change, 38: 195–204.
18. de Chazal, J. & Rounsevell, M.D.A. 2009. Land-use and climate change within assessments of biodiversity change: a review. Global Environmental Change, 19(2): 306–315.
19. Costa-Font, J. & Mas, N. 2016. 'Globesity'? The effects of globalization on obesity and caloric intake. Food Policy, 64: 121–132.
20. Costinot, A. & Donaldson, D. 2016. How large are the gains from economic integration? Theory and evidence from U.S. agriculture, 1880-1997. National Bureau of Economic Research. (also available at https://www.nber.org/papers/w22946)
21. Costinot, A., Donaldson, D. & Smith, C. 2016. Evolving comparative advantage and the impact of climate change in agricultural markets: evidence from 1.7 million fields around the world. Journal of Political Economy, 124(1): 205–248.
22. Cowling, K., Thow, A.M. & Pollack Porter, K. 2018. Analyzing the impacts of global trade and investment on non-communicable diseases and risk factors: a critical review of methodological approaches used in quantitative analyses. Globalization and Health, 14(1): 53.
23. Cuevas García-Dorado, S., Cornselsen, L., Smith, R. & Walls, H. 2019. Economic globalization, nutrition and health: a review of quantitative evidence. Globalization and Health, 15(1): 15.
24. Cui, H.D., Kuiper, M., van Meijl, H. & Tabeau, A. 2018. Climate change and global market integration: implications for global economic activities, agricultural commodities and food security. The State of Agricultural Commodity Markets (SOCO) 2018: Background paper. Rome. 42 pp.
25. Dalin, C. & Rodríguez-Iturbe, I. 2016. Environmental impacts of food trade via resource use and greenhouse gas emissions. Environmental Research Letters, 11(3): 035012.
26. Davis, K.F., Downs, S. & Gephart, J.A. 2021. Towards food supply chain resilience to environmental shocks. Nature Food, 2(1): 54–65.

27. Deng, G., Lu, F., Wu, L. & Xu, C. 2021. Social network analysis of virtual water trade among major countries in the world. Science of The Total Environment, 753: 142043.
28. Dithmer, J. & Abdulai, A. 2017. Does trade openness contribute to food security? A dynamic panel analysis. Food Policy, 69: 218–230.
29. Dixit, A. 1985. Chapter 6 Tax policy in open economies. In: A.J. Auerbach & M.S. Feldstein, eds. Handbook of public economics, pp. 313–374. Elsevier. (also available at https://www.sciencedirect.com/science/article/pii/S1573442085800094)
30. Dreher, A. 2006. Does globalization affect growth? Evidence from a new index of globalization. Applied Economics, 38(10): 1091–1110.
31. Escobar, N., Tizado, E.J., zu Ermgassen, E.K.H.J., Löfgren, P., Börner, J. & Godar, J. 2020. Spatially-explicit footprints of agricultural commodities: mapping carbon emissions embodied in Brazil's soy exports. Global Environmental Change, 62: 102067.
32. FAO. 2016. The State of Agricultural Commodity Markets 2015-16. Trade and food security: achieving a better balance between national priorities and the collective good. Rome, FAO. 89 pp. (also available at http://www.fao.org/publications/soco/the-state-of-agricultural-commodity-markets-2015-16/en/)
33. FAO. 2018a. The State of Agricultural Commodity Markets 2018. Agricultural trade, climate change and food security. Rome, FAO. 112 pp. (also available at http://www.fao.org/3/I9542EN/i9542en.pdf)
34. FAO. 2018b. Trade and nutrition technical note. Trade policy technical note No. 21. Rome, FAO. 8 pp. (also available at http://www.fao.org/3/I8545EN/i8545en.pdf)
35. FAO. 2018c. The future of food and agriculture - Alternative pathways to 2050. Rome, FAO. 224 pp. (also available at http://www.fao.org/3/I8429EN/i8429en.pdf)
36. FAO. 2020a. Understanding international harmonization of pesticide maximum residue limits with Codex standards: a case study on rice. Rome, FAO. 108 pp. (also available at http://www.fao.org/documents/card/en/c/cb0463en)
37. FAO. 2020b. The State of Agricultural Commodity Markets 2020. Agricultural markets and sustainable development: Global value chains, smallholder farmers and digital innovations. Rome, FAO. 164 pp. (also available at https://doi.org/10.4060/cb0665en)
38. FAO & AUC. 2021. Framework for boosting intra-African trade in agricultural commodities and services. Addis Ababa, FAO and AUC. 80 pp. (also available at https://doi.org/10.4060/cb3172en)
39. Farrokhi, F. & Pellegrina, H.S. 2020. Global trade and margins of productivity in agriculture. National Bureau of Economic Research. (also available at https://www.nber.org/papers/w27350)
40. Fleming, D.A. & Abler, D.G. 2013. Does agricultural trade affect productivity? Evidence from Chilean farms. Food Policy, 41: 11–17.
41. Geyik, O., Hadjikakou, M., Karapinar, B. & Bryan, B.A. 2021. Does global food trade close the dietary nutrient gap for the world's poorest nations? Global Food Security, 28: 100490.
42. Giuntella, O., Rieger, M. & Rotunno, L. 2020. Weight gains from trade in foods: evidence from Mexico. Journal of International Economics, 122: 103277.
43. Goryakin, Y., Lobstein, T., James, W.P.T. & Suhrcke, M. 2015. The impact of economic, political and social globalization on overweight and obesity in the 56 low and middle income countries. Social Science & Medicine, 133: 67–76.
44. Götz, L., Glauben, T. & Brümmer, B. 2013. Wheat export restrictions and domestic market effects in Russia and Ukraine during the food crisis. Food Policy, 38: 214–226.
45. Gouel, C. & Laborde, D. 2021. The crucial role of domestic and international market-mediated adaptation to climate change. Journal of Environmental Economics and Management, 106: 102408.
46. Grant, J.H. 2013. Is the growth of regionalism as significant as the headlines suggest? Lessons from agricultural trade. Agricultural Economics, 44(1): 93–109.
47. Grossman, G.M. & Helpman, E. 1991. Trade, knowledge spillovers, and growth. European Economic Review, 35(2): 517–526.
48. Grossman, G.M. & Krueger, A.B. 1991. Environmental impacts of a North American Free Trade Agreement. National Bureau of Economic Research. (also available at https://www.nber.org/papers/w3914).
49. Gutierrez, L. 2002. Why is agricultural labour productivity higher in some countries than others? Agricultural Economics Review, 3(1): 58–72.
50. Gwartney, J., Lawson, R. & Hall, J. 2013. The economic freedom of the world: 2013 annual report. Fraser Institute.
51. Hart, J., Miljkovic, D. & Shaik, S. 2015. The impact of trade openness on technical efficiency in the agricultural sector of the European Union. Applied Economics, 47(12): 1230–1247.
52. Havlík, P., Valin, H., Gusti, M., Schmid, Erwin, Leclère, D., Forsell, N., Herrero, M., Khabarov,

N., Mosnier, A., Cantele, M. & Obersteiner, M. 2015. Climate change impacts and mitigation in the developing world. Policy Research Working Paper. World Bank Group. 56 pp. (also available at http://documents.worldbank.org/curated/en/866881467997281798/pdf/WPS7477.pdf)
53. Henle, K., Alard, D., Clitherow, J., Cobb, P., Firbank, L., Kull, T., McCracken, D., Moritz, R.F.A., Niemelä, J., Rebane, M., Wascher, D., Watt, A. & Young, J. 2008. Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe–A review. Agriculture, Ecosystems & Environment, 124(1): 60–71.
54. Irwin, D.A. 2019. Does trade reform promote economic growth? A review of recent evidence. National Bureau of Economic Research. (also available at https://www.nber.org/papers/w25927)
55. van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E. & Wolf, J. 2008. Integrated assessment of agricultural systems – A component-based framework for the European Union (SEAMLESS). Agricultural Systems, 96(1–3): 150–165.
56. Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclère, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Van Lipzig, N. & Maertens, M. 2020. Global hunger and climate change adaptation through international trade. Nature Climate Change, 10(9): 829–835.
57. Kalkuhl, M., von Braun, J. & Torero, M. 2016. Volatile and extreme food prices, food security, and policy: an overview. In: M. Kalkuhl, J. von Braun & M. Torero, eds. Food price volatility and its implications for food security and policy, pp. 3–31. Cham, Springer International Publishing. (also available at https://doi.org/10.1007/978-3-319-28201-5_1)
58. Knutson, A. & de Soysa, I. 2019. Does social globalisation through access to information communication technologies drive obesity among youth? An empirical analysis, 1990–2013. Global Public Health, 14(12): 1911–1926.
59. Krivonos, E. & Kuhn, L. 2019. Trade and dietary diversity in Eastern Europe and Central Asia. Food Policy, 88: 101767.
60. von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D. & van Meijl, H. 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. Agricultural Economics, 45(1): 3–20.
61. Lawson, R.A., Murphy, R.H. & Williamson, C.R. 2016. The relationship between income, economic freedom, and BMI. Public Health, 134: 18–25.
62. Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L. & Geschke, A. 2012. International trade drives biodiversity threats in developing nations. Nature, 486(7401): 109.
63. Lin, T.K., Teymourian, Y. & Tursini, M.S. 2018. The effect of sugar and processed food imports on the prevalence of overweight and obesity in 172 countries. Globalization and Health, 14(1): 35.
64. Marquardt, S.G., Guindon, M., Wilting, H.C., Steinmann, Z.J.N., Sim, S., Kulak, M. & Huijbregts, M.A.J. 2019. Consumption-based biodiversity footprints – Do different indicators yield different results? Ecological Indicators, 103: 461–470.
65. Martin, W. 2018. A research agenda for international agricultural trade. Applied Economic Perspectives and Policy, 40(1): 155–173.
66. Martin, W. & Anderson, K. 2012. Export restrictions and price insulation during commodity price booms. American Journal of Agricultural Economics, 94(2): 422–427.
67. Mary, S. 2019. Hungry for free trade? Food trade and extreme hunger in developing countries. Food Security, 11(2): 461–477.
68. Mary, S. & Stoler, A. 2021. Does agricultural trade liberalization increase obesity in developing countries? Review of Development Economics.
69. Miljkovic, D., de Miranda, S.H.G., Kassouf, A.L. & Oliveira, F.C.R. 2018. Determinants of obesity in Brazil: the effects of trade liberalization and socio-economic variables. Applied Economics, 50(28): 3076–3088.
70. Montalbano, P. & Nenci, S. 2020. The effects of global value chain (GVC) participation on the economic growth of the agricultural and food sectors. Background paper for The State of Agricultural Commodity Markets (SOCO) 2020. Rome, FAO. 60 pp. (also available at http://www.fao.org/documents/card/en/c/cb0714en)
71. Moran, D. & Kanemoto, K. 2017. Identifying species threat hotspots from global supply chains. Nature Ecology & Evolution, 1(1): 0023.
72. Morin, J.-F., Dür, A. & Lechner, L. 2018. Mapping the trade and environment nexus: insights from a new data set. Global Environmental Politics, 18(1): 122–139.
73. Nath, I.B. 2020. The food problem and the aggregate productivity consequences of climate change. National Bureau of Economic Research. (also available at https://www.nber.org/papers/w27297)

74. Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Lampe, M.V., Lotze-Campen, H., d'Croz, D.M., Meijl, H. van, Mensbrugghe, D. van der, Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A. & Willenbockel, D. 2014. Climate change effects on agriculture: economic responses to biophysical shocks. Proceedings of the National Academy of Sciences, 111(9): 3274–3279.
75. Oberlander, L., Disdier, A.-C. & Etilé, F. 2017. Globalisation and national trends in nutrition and health: a grouped fixed-effects approach to intercountry heterogeneity. Health Economics, 26(9): 1146–1161.
76. OECD. 2015. The economic consequences of climate change. Paris, OECD Publishing. 140 pp. (also available at http://dx.doi.org/10.1787/9789264235410-en)
77. Olper, A., Curzi, D. & Raimondi, V. 2017. Imported intermediate inputs and firms' productivity growth: evidence from the food industry. Journal of Agricultural Economics, 68(1): 280–300.
78. Ortiz, A.M.D., Outhwaite, C.L., Dalin, C. & Newbold, T. 2021. A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. One Earth, 4(1): 88–101.
79. Pace, M.L. & Gephart, J.A. 2017. Trade: a driver of present and future ecosystems. Ecosystems, 20(1): 44–53.
80. Pastor, A.V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P. & Ludwig, F. 2019. The global nexus of food–trade–water sustaining environmental flows by 2050. Nature Sustainability, 2(6): 499–507.
81. Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S. & Wood, R. 2019. Agricultural and forestry trade drives large share of tropical deforestation emissions. Global Environmental Change, 56: 1–10.
82. Phalan, B., Onial, M., Balmford, A. & Green, R.E. 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science, 333(6047): 1289–1291.
83. Qiang, W., Niu, S., Liu, A., Kastner, T., Bie, Q., Wang, X. & Cheng, S. 2020. Trends in global virtual land trade in relation to agricultural products. Land Use Policy, 92: 104439.
84. Rapsomanikis, G. 2011. Price transmission and volatility spillovers in food markets. In: A. Prakash, ed. Safeguarding food security in volatile global markets, pp. 144–163. Rome, FAO.
85. Reilly, J. 1995. Climate change and global agriculture: recent findings and issues. American Journal of Agricultural Economics, 77(3): 727–733.
86. Remans, R., Wood, S.A., Saha, N., Anderman, T.L. & DeFries, R.S. 2014. Measuring nutritional diversity of national food supplies. Global Food Security, 3(3): 174–182.
87. Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J.A. 2009. A safe operating space for humanity. Nature, 461(7263): 472–475.
88. Rodrik, D. 1987. Policy targeting with endogenous distortions: theory of optimum subsidy revisited. The Quarterly Journal of Economics, 102(4): 903–911.
89. Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E.T., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., Tubiello, F.N., Xu, Y., Mencos Contreras, E. & Portugal-Pereira, J. 2020. Climate change responses benefit from a global food system approach. Nature Food, 1(2): 94–97.
90. Roux, N., Kastner, T., Erb, K.-H. & Haberl, H. 2021. Does agricultural trade reduce pressure on land ecosystems? Decomposing drivers of the embodied human appropriation of net primary production. Ecological Economics, 181: 106915.
91. Rude, J. & An, H. 2015. Explaining grain and oilseed price volatility: the role of export restrictions. Food Policy, 57: 83–92.
92. Santeramo, F.G. & Lamonaca, E. 2019. The effects of non-tariff measures on agri-food trade: a review and meta-analysis of empirical evidence. Journal of Agricultural Economics, 70(3): 595–617.
93. Schmidhuber, J. & Tubiello, F.N. 2007. Global food security under climate change. Proceedings of the National Academy of Sciences, 104(50): 19703–19708.
94. Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Krause, M. & Weindl, I. 2012. Trading more food: implications for land use, greenhouse gas emissions, and the food system. Global Environmental Change, 22(1): 189–209.
95. Schmitz, C., Kreidenweis, U., Lotze-Campen, H., Popp, A., Krause, M., Dietrich, J.P. & Müller, C. 2015. Agricultural trade and tropical deforestation:

interactions and related policy options. Regional Environmental Change, 15(8): 1757–1772.
96. Sheldon, I.M., Chow, D.C.K. & McGuire, W. 2018. Trade liberalization and constraints on moves to protectionism: multilateralism vs. regionalism. American Journal of Agricultural Economics, 100(5): 1375–1390.
97. Smith, O., Momber, G., Bates, R., Garwood, P., Fitch, S., Pallen, M., Gaffney, V. & Allaby, R.G. 2015. Sedimentary DNA from a submerged site reveals wheat in the British Isles 8000 years ago. Science, 347(6225): 998–1001.
98. de Soysa, I. & de Soysa, A.K. 2018. Do globalization and free markets drive obesity among children and youth? An empirical analysis, 1990–2013. International Interactions, 44(1): 88–106.
99. Sporchia, F., Taherzadeh, O. & Caro, D. 2021. Stimulating environmental degradation: a global study of resource use in cocoa, coffee, tea and tobacco supply chains. Current Research in Environmental Sustainability, 3: 100029.
100. Stevanović, M., Popp, A., Lotze-Campen, H., Dietrich, J.P., Müller, C., Bonsch, M., Schmitz, C., Bodirsky, B.L., Humpenöder, F. & Weindl, I. 2016. The impact of high-end climate change on agricultural welfare. Science Advances, 2(8): e1501452.
101. Sun, J., Mooney, H., Wu, W., Tang, H., Tong, Y., Xu, Z., Huang, B., Cheng, Y., Yang, X., Wei, D., Zhang, F. & Liu, J. 2018. Importing food damages domestic environment: evidence from global soybean trade. Proceedings of the National Academy of Sciences, 115(21): 5415–5419.
102. Sun, J.X., Yin, Y.L., Sun, S.K., Wang, Y.B., Yu, X. & Yan, K. 2021. Review on research status of virtual water: the perspective of accounting methods, impact assessment and limitations. Agricultural Water Management, 243: 106407.
103. Tadesse, G., Algieri, B., Kalkuhl, M. & von Braun, J. 2014. Drivers and triggers of international food price spikes and volatility. Food Policy, 47: 117–128.
104. Teignier, M. 2018. The role of trade in structural transformation. Journal of Development Economics, 130: 45–65.
105. Thow, A.M., Jones, A., Hawkes, C., Ali, I. & Labonté, R. 2018. Nutrition labelling is a trade policy issue: lessons from an analysis of specific trade concerns at the World Trade Organization. Health Promotion International, 33(4): 561–571.
106. Thow, A.M. & Nisbett, N. 2019. Trade, nutrition, and sustainable food systems. The Lancet, 394(10200): 716–718.
107. Tinbergen, J. 1952. On the theory of economic policy. (also available at https://repub.eur.nl/pub/15884/)
108. Tombe, T. 2015. The missing food problem: trade, agriculture, and international productivity differences. American Economic Journal: Macroeconomics, 7(3): 226–258.
109. Traverso, S. & Schiavo, S. 2020. Fair trade or trade fair? International food trade and cross-border macronutrient flows. World Development, 132: 104976.
110. Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. & Whitbread, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biological Conservation, 151(1): 53–59.
111. United Nations Economic Commission for Africa. 2018. An empirical assessment of the African Continental Free Trade Area modalities on goods. Addis Ababa, United Nations Economic Commission for Africa. 5 pp. (also available at https://repository.uneca.org/handle/10855/41828)
112. United Nations Economic Commission for Africa & TradeMark East Africa. 2020. Creating a unified regional market. Towards the implementation of the African Continental Free Trade Area in East Africa. Kigali, United Nations Economic Commission for Africa and TradeMark East Africa. 144 pp. (also available at https://archive.uneca.org/sites/default/files/PublicationFiles/tmea_afcfta_report_5_june_2020.pdf)
113. Viner, J. 1950. The customs union issue. Oxford University Press.
114. Vogli, R.D., Kouvonen, A., Elovainio, M. & Marmot, M. 2014. Economic globalization, inequality and body mass index: a cross-national analysis of 127 countries. Critical Public Health, 24(1): 7–21.
115. Wheeler, T. & von Braun, J. 2013. Climate change impacts on global food security. Science, 341(6145): 508–513.
116. Wieck, C. 2018. International trade rules for food safety and food quality. In: K. Meilke & T. Josling, eds. Handbook of international food and agricultural policies, pp. 277–308. World Scientific. (also available at https://www.worldscientific.com/doi/abs/10.1142/9789813226487_0011)
117. Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., Mensbrugghe, D. van der, Anne Biewald, Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., Christoph Müller, Popp, A., Robertson, R., Robinson, S., Meijl, H. van & Willenbockel, D. 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environmental Research Letters, 10(8): 085010.
118. Wood, S., Smith, M., Fanzo, J., Remans, R. & DeFries, R. 2018. Trade and the equitability of global food nutrient distribution. Nature Sustainability, 1: 34–37.

119. WTO. 2021. WTO | Regional Trade Agreements gateway [online]. [Cited 15 April 2021]. https://www.wto.org/english/tratop_e/region_e/region_e.htm
120. Zurek, M., Hebinck, A., Leip, A., Vervoort, J., Kuiper, M., Garrone, M., Havlík, P., Heckelei, T., Hornborg, S., Ingram, J., Kuijsten, A., Shutes, L., Geleijnse, J.M., Terluin, I., Van 't Veer, P., Wijnands, J., Zimmermann, A. & Achterbosch, T. 2018. Assessing sustainable food and nutrition security of the EU food system— An integrated approach. Sustainability, 10(11): 4271.

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Report (Draft)
prepared by the Scientific Group for the Food Systems Summit
July 2021

THE TRUE COST AND TRUE PRICE OF FOOD

by Sheryl Hendriks, Adrian de Groot Ruiz, Mario Herrero Acosta, Hans Baumers, Pietro Galgani, Daniel Mason-D'Croz, Cecile Godde, Katharina Waha, Dimitra Kanidou, Joachim von Braun, Mauricio Benitez, Jennifer Blanke, Patrick Caron, Jessica Fanzo, Friederike Greb, Lawrence Haddad, Anna Herforth, Danie Jordaan, William Masters, Claudia Sadoff, Jean-François Soussana, Maria Cristina Tirado, Maximo Torero and Matthew Watkins

THE AUTHORS ARE

Sheryl L. Hendriks (South Africa) Member of the Scientific Group, Professor of Food Security, Department of Agricultural Economics, Extension and Rural Development, University of Pretoria.
Adrian de Groot Ruiz (Netherlands), Executive Director Impact Institute, director True Price
Mario Herrero Acosta (Costa Rica), Member of the Scientific Group, Chief Research Scientist of Agriculture and Food, The Commonwealth Scientific and Industrial Research Organisation (CSIRO).
Hans Baumers (Belgium), Senior data analyst, Impact Institute.
Pietro Galgani (Italy), Lead Methodology Development, True Price, R&D manager Impact Institute.
Daniel Mason-D'Croz (Colombia/USA), Senior Research Scientist of Agriculture and Food, The Commonwealth Scientific and Industrial Research Organisation (CSIRO).
Cecile Godde (France/Australia), Research Scientist, Agriculture and Food, The Commonwealth Scientific and Industrial Research Organisation (CSIRO).
Katharina Waha (Germany/Australia), Senior Research Scientist, Agriculture and Food, The Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Dimitra Kanidou (Greece), Analyst, Impact Institute.
Joachim von Braun (Germany), Chair of the Scientific Group. Director of the Center for Development Research (ZEF), Bonn University, and Professor for economic and technological change.
Mauricio Benitez (Mexico), responsAbility Investments AG.
Jennifer Blanke (Switzerland), Non-Executive Director, ARC Ltd.
Patrick Caron (France), Member of the Scientific Group, Cirad, Vice-President of the University of Montpellier, Director of the Montpellier Advanced Knowledge Institute on Transitions
Jessica Fanzo (USA), Johns Hopkins University
Friederike Greb (Germany), World Food Programme.
Lawrence Haddad (UK), Lead: Food Systems Summit Action Track 1, Executive Director of the Global Alliance for Improved Nutrition (GAIN).
Anna Herforth (USA), Independent Consultant.
Danie Jordaan (South Africa), Department of Agricultural Economics, Extension and Rural Development, University of Pretoria
William A Masters (USA), Friedman School of Nutrition and Department of Economics, Tufts University.
Claudia Sadoff (USA), Member of the Scientific Group, Executive Management Team Convener and Managing Director, Research Delivery and Impact, of the Consultative Group on International Agricultural Research.
Jean-François Soussana (France), Member of the Scientific Group, is Vice-President for international at the French national research institute for agriculture, food and environment (INRAE).
Maria Cristina Tirado (USA). Adjunct Associate Professor, School of Public Health UCLA, Director of International Climate Initiatives at the LMU Center for Urban Resilience.
Maximo Torero (Peru), Ex-officio Member of the Scientific Group, Chief Economist, Food and Agriculture Organization of the United Nations (FAO).
Matthew Watkins (UK), Manager- Food Reform for Sustainability and Health /FReSH), WBCSD (World Business Council for Sustainable Development)

With assistance from **Prisca Atieno** and **Valiant Odhiambo** (Kenya), Postgraduate Assistants, Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, South Africa

ABSTRACT

Ensuring sustainable food systems requires vastly reducing its environmental and health costs while making healthy and sustainable food affordable to all. One of the central problems of current food systems is that many of the costs of harmful foods are externalized, i.e. they are not reflected in market prices. At the same time, the benefits of healthful foods are not appreciated. Due to externalities, sustainable and healthy food is often less affordable to consumers and profitable for businesses than unsustainable and unhealthy food. Externalities and other market failures lead to unintended consequences for present and future generations, destroying nature and perpetuating social injustices such as underpay for workers, food insecurity, illness, premature death and other harms. We urgently need to address the fundamental causes of these problems. This brief sets out the results of an analysis to determine the current cost of externalities in the food system and the potential impact of a shift in diets to more healthy and sustainable production and consumption patterns. The current externalities were estimated to be almost double (19.8 trillion USD) the current total global food consumption (9 trillion USD). These externalities accrue from seven trillion USD (range 4-11) in environmental costs, 11 trillion USD (range 3-39) in costs to human life and one trillion USD (range 0.2-1.7) in economic costs. This means that food is roughly one-third cheaper than it would be if these externalities were included in market pricing. More studies are needed to quantify the costs and benefits of food systems to support a global shift to more sustainable and healthy diets. However, the evidence presented in this brief points to the urgent need for a system reset to account for these 'hidden costs in food systems and calls for bold actions to redefine food prices and the incentives for producing and consuming healthier and more sustainable diets. The first step to correct for these 'hidden costs' is to redefine the value of food through true cost accounting (TCA) to address externalities and other market failures. TCA reveals the true value of food by making the benefits of affordable and healthy food visible and revealing the costs of damage to the environment and human health. The second corrective step is true pricing: incorporating externalities in prices to align market incentives with social values. Appropriate safety nets to boost consumer purchasing power and the enforcement of rights and regulations should also be part of true pricing to ensure that affordable and healthy food is accessible to all. Such actions will conserve the environment and simultaneously meet fundamental universal human rights and accelerate progress towards achieving development goals.

1. INTRODUCTION

The vision of the UN Food Systems Summit is to "launch bold new actions, solutions and strategies to deliver progress on all 17 Sustainable Development Goals (SDGs), each of which relies on healthier, more sustainable and more equitable food systems" (UN, 2020). The Summit seeks to transform the way the world produces, consumes and thinks about food build a just and resilient world where no one is left behind (UN, 2020). In various Summit platform discussions, questions have arisen relating to (a) the true cost of the food we eat, (b) what costs would be involved in shifting to more sustainable patterns of production and consumption, (c) who would bear the cost of these changes and (d) what the implications are for the poorest consumers. Addressing these hidden externalities would be a significant, bold action.

Ensuring sustainable food systems entails ensuring that food systems provide affordable and healthy food to all people while respecting planetary and social boundaries. Current food systems are not sustainable. They generate substantial environmental, social and health costs while failing to provide affordable food to all (FAO et al., 2020). For example:

- The emissions associated with pre- and post-production activities in the global food system are estimated to be 21-37% of total net anthropogenic GHG emissions (IPCC, 2019),
- The majority of the global working poor work in agriculture (World Bank, 2016),
- 690 million people were undernourished in 2019 (FAO et al., 2020), and
- More than 10 million lives are lost annually due to unhealthy eating patterns (GBD, 2019).

A transition to sustainable food systems will reduce their environmental, social and health costs while making healthy food affordable to all. Researchers have only recently begun investigating what dietary changes will be necessary to keep food systems within planetary boundaries (Herrero et al., 2017, Rockström et al., 2009). Even more recently, the question has arisen of how changes in the food system and their resultant impacts on environments in which consumers acquire foods (food environments) affect our health, particularly the incidence of obesity and non-communicable diseases (Willet et al., 2019). For example, the EAT-Lancet report estimated that a transformation to healthy diets by 2050 would require substantial dietary shifts. This will include reducing the consumption of:

- Foods with added sugars (including harmful non-nutritive sweeteners);

- Refined grains (that can cause diabetes);
- Added sodium (that can cause hypertension);
- Harmful fats (especially harmful trans fats, and to a lesser degree, other solid fats linked to cardiovascular disease); and
- Processed meats (associated with cancer).

Increasing the consumption of healthy, protective foods such as fruits and vegetables, legumes, nuts and seeds (Willett et al., 2019) will address multiple health-related issues. These protective foods are needed for their phytochemicals and fiber that may be absent from other foods. Often unhealthy foods displace healthy alternatives (such as fruit, legumes, nuts, seeds and vegetables and beneficial forms of primary processing such as fermentation) that may be less convenient (Masters et al., 2021) and less marketed and therefore under-consumed.

Effective game-changing strategies[1] to achieve sustainable food systems should arguably not ony treat the symptoms of the problem. Solutions should also address the root causes of why food systems impose environmental and health costs and fail to provide sufficient quantities of beneficial foods in the first place. One major root cause is that these costs and benefits of production and consumption are externalized due to how markets are designed. These externalities are not reflected in market prices (Baker et al., 2020) and have no economic 'currency'. As a result externalities are hidden effects of choices of market players, and make sustainable and healthy food less affordable for consumers and less profitable for producers. Historically the choices of all stakeholders and business profits have been based on market prices and recorded in economic statistics such as gross domestic product (GDP). External costs and benefits can also be documented in statistics on mortality and disease, climate change and pollution. However, the link between market activity and those social or environmental harms is not directly visible or reflected in the incentives that drive economic systems. As a result, the economic value of food, which drives economic choices by businesses, consumers and governments, is highly distorted. By providing distorted information and perverse (often unintended) incentives against affordable, sustainable and healthy food, externalities constitute a significant barrier to attaining sustainable food systems. Moreover, even with a full cost approach, there are likely trade-offs across the health and sustainability considerations. There is considerable diversity in regional food systems and their externalities.

First, internalizing the externalities of the food system requires redefining the value of food by measuring and costing these externalities through 'True Cost Accounting' approaches. Secondly, the economics of food needs to be redesigned to explore pathways to internalize these externalities in prices, namely through true pricing. A price-based adjustment would be more inclusive than imposing third-party harm (abatements) or penalties. When combined with public funding mechanisms, true pricing could make sustainable and healthy food affordable and profitable.

At the request of the Scientific Group of the UN Food Systems Summit, a working group set out to investigate the true costs of food and propose possible actions to address the problem. This brief aims to inform food system stakeholders about how they can grasp an opportunity based on the most recent scientific insights in this young and emerging field of analysis. Section 2 summarizes the problem of externalities. Section 3 describes how TCA can be used to redefine the value of food. Section 4 sets out how true pricing can be used to redesign the economics of food. Section 5 provides an analysis of the current true environmental and health costs of food at the global level based on research from the working group. Section 6 outlines the potential benefits of dietary transitions. Section 7 discusses the implications of the analysis for the design of true pricing mechanisms. Section 8 concludes and presents recommendations.

2. THE EXTERNALITIES AS BARRIERS TO SUSTAINABLE FOOD SYSTEMS

Externalities refer to "situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided" (OECD, 2013). Externalities can arise when people are affected by market choices of others that they have no say in (Laffont, 2008). For example, greenhouse gas emissions from one person's actions affect people far away and future generations who have no say in those decisions. Externalities can

1 The UNFSS definition of a 'game-changing and systemic solution' is a feasible action, based on evidence, best practice or a thorough conceptual framework that would shift operational models or underlying rules, incentives and structures that shape food systems, acting on multiple parts of – or across – the food system, to advance global goals which can be sustained over time. The key criteria that a 'game-changing and systemic'

also be beneficial, such as disease prevention that reduces health care costs. There are other price-related market failures, that cause prices to lead to inefficient allocation of resources. In addition, to monopoly and monopsony, a lack of information or behavioral biases, for example around health effects can lead consumers to ignore costs and benefits of their decisions (Gruber & Kőszegi, 2001; Wang & Sloan, 2018). Due to missing markets, the well-being effects of affordable healthy food on the poor will not translate to higher prices and drive the supply of more healthy food (UNLPE, 2012).

Externalities arise from several elements in the food system (see Table 1). The boundary between social and human capital is defined differently across frameworks and health externalities can also be classified as human capital (TEEB, 2018; IIRC, 2006). Health externalities can also be classified as human capital (TEEB, 2018; IIRC, 2006). There is a considerable variation in costs between food products and regions (see Wageningen University (2017) for examples of variation in animal value chains). In some cases, traditional practices of animal husbandry can have positive effects on natural capital (Baltussen et al., 2019). Commodities involving production by smallholders in developing countries (such as cocoa or coffee) tend to have higher external social costs, including underearning for farmers (IDH, 2014).

Externalities create significant problems in food systems. The first problem is that externalities prevent societies from achieving their full potential by distorting the information about the value of food conveyed by market prices (Gemmill-Herren, 2021). The market price of products does not reflect its true costs and benefits. Furthermore, the value of companies and their decisions reflect expected future profits - the difference between the sum of the cost of outputs minus the sum of the cost of all inputs, including labor (OECD, 2002), all valued at market prices. If a company contributes to climate change, underpays workers or enables healthy and affordable food, this is not reflected in its profit (Serafeim et al., 2019). As the financial returns of companies are based on their (expected) profits, the financial value of investments does not reflect the actual value that these investments benefit society (Serafeim et al., 2019). The economic value of the food sector is measured by its contribution to GDP, which the sum of all companies' value-added - the value of

Table 1 Summary of the key externalities in food systems

Type of externality	Examples of externalities	Endpoint impact(s)
Environmental[1] (effects on natural capital)	Air, water and soil pollution GHG emissions Land use Overuse of renewable resources Soil depletion Use of scarce materials Water use	Contribution to climate change, health effects, depletion of abiotic resources, depletion of biotic resources including ecosystem services and biodiversity.
Social[2] (effects on social rights and human & social capital)	Animal welfare Child and forced labor Discrimination and harassment High and variable prices Training Underpayment and underearning	Poverty, well-being, food security and human skills.
Health[3] (effects on human health)	Antimicrobial resistance Undernutrition Unhealthy diet composition Zoonoses	Human life (mortality and the quality of life), Economic (medical costs, informal care, lost working days)
Economic[4] (effects on financial, manufactured and intellectual capital)	Food waste Tax evasion	Increased food demand, and a decrease in public funds

Sources:
[1] FAO, 2015; NCC, 2015; Baltussen et al., 2016; Allen & Prosperi, 2016; Nkonya et al., 2016; TEEB, 2018; 2019; Dalin & Outhwaite, 2019; FOLU, 2019; Galgani et al, 2021.
[2] Baltussen et al., 2016; Westhoek et al., 2016; IDH, 2016; WBCSD, 2018; Jaffa et al., 2019; True Price, 2020a, Galgani et al, 2021.
[3] Wageningen University, 2017; FOLU,2019; TEEB, 2018; GBD, 2019; FAO et al., 2020.
[4] FAO, 2015; TEEB, 2018; 2019; Impact Institute, 2020; FAO et al., 2020.

output minus the value of intermediate consumption measured at market prices (OECD, 2001). Hence, the degree to which the food systems contribute to climate change, deforestation or poor health is not factored into crucial economic indicators for policy-makers (Stiglitz et al., 2018), and externalities, therefore, lead countries to have lower average living standards than would otherwise be possible.

A second problem with (negative) externalities is social injustice. The existing arrangement of property rights, institutions and infrastructure were constructed over time, reflecting past choices of those in power who sometimes neglected or actively harmed marginalized groups, including women and girls, indigenous and minority populations, migrant workers and other communities. Environmental harm such as air and water pollution are often concentrated in places inhabited by marginalized groups. Unhealthy products are often marketed most intensively to vulnerable populations such as children.

The result is a variety of involuntary harms that may include severe rights violations: forced labor, harassment of women or underpayment in the agricultural sector and breach the rights of people making our food. A lack of affordable food is also a breach of the right to food for consumers. The erosion of natural capital breaches the rights of future generations to decent livelihoods (United Nations, 1972).

The third problem with externalities is that they inadvertently reward unsustainable, unaffordable and unhealthy food production and consumption. As natural, health and social costs are externalized, it is more profitable to produce unsustainable and unhealthy food. Child labor, forced labor and underpaid workers represent cheap labor, consuming natural resources without replenishing those provides cheap inputs and not containing pollution saves costs. At the same time, adding calories, salt, poor quality fats, sugars and harmful sugar alternatives to food items and promoting such foods can increase sales despite the negative effects on health (Stuckler et al., 2012). Food safety adds to the harmful effects on health, especially in developing countries (Devleesschauwer et al., 2018). One reason is that there is neurobehavioral evidence that some unhealthy foods elicit higher reward responses in the brain than healthy foods (Banerjee et al., 2020).

In the same way, encouraging high levels of food waste, e.g. through appealing packaging, can increase sales. Moreover, firms have no incentive to make healthy food affordable. Businesses set prices to optimize their business profit (Laffont, 2008), sometimes using inflated prices as signals of healthy food (Haws et al., 2016). As a result, sustainable and healthy food is more expensive to buy than unhealthy food (Stuckler et al., 2012).

Given that global capital markets allocate capital based on financial returns, most capital will flow to the most successful companies in externalizing costs to optimize profit (Serafeim et al., 2019). In an economy where consumers maximize purchasing power, businesses maximize profits. In addition, investors maximize returns, leading to the underproduction of food leading to waste, overuse of natural resources and overconsumption of unhealthy food (Gemill-Herren et al., 2021).

In summary, externalities form a significant barrier to the transition to sustainable food systems. It is difficult to imagine how policies aiming to foster sustainable food systems will be successful in an economic system where the erosion of natural capital, breaches of human rights, and unhealthy food are permissible and strongly incentivized.

3. TRUE COST ACCOUNTING: REDEFINING THE VALUE OF FOOD

A first step to address externalities is to expose them and redefine the value of food. This can be realized by True Cost Accounting (TCA), a tool for the systemic measurement and valuation of environmental, social, health and economic costs and benefits to facilitate sustainable choices by governments and food system stakeholders (Baker et al., 2020; Gemmill-Herren et al., 2021). TCA can serve different purposes, where different actors have different applications (Baker et a.l, 2020):

- *Governments* can integrate TCA into local, national or regional policy and budgeting. For example, Brazil, China, Columbia, India, Indonesia, Kenya, Malaysia, Mexico, Tanzania, and Thailand have applied TCA through the TEEBAgriFood framework's participatory process to bring stakeholders together to identify agricultural land-use policies that would benefit from the valuation of ecosystem services (Baker et al., 2020). An interim TCA assessment in Indonesia contributed to agroforestry being included in the country's 2020 five-year development plan (Baker et al., 2020).
- *Businesses* can use these structured assessments to minimize negative impacts and enhance positive benefits across value chains (Serafeim et al., 2019; WBCSD, 2021a). Companies can use TCA to produce impact statements or impact weighted

accounts (monetized, multi-capital, multi-stakeholder accounts of all material business impacts, including true costs and benefits) (Baker et al., 2020) and manage their externalities (NCC, 2016; Impact Institute, 2020) .

- *Financial institutions* use TCA for reporting, impact investment and risk assessment (WBCSD, 2021; Impact Institute, 2020), and obtain assurance on their published impact statement (Schramade, 2020).[2]
- *Farmers* can use TCA as a means to account for the costs and benefits of their agricultural practices (Jones, 2020). Various initiatives recognize farmers, peasants, indigenous peoples, pastoralists, and other food producers as important stewards of biocultural landscapes (Baker et al., 2020; Gemmill-Herren, 2021).
- *Consumers* can use TCA to become aware of the environmental and social externalities embedded in the food they buy (Lord, 2020). Many labelling schemes incorporate TCA information to strengthen the transparency they provide to consumers (Gemmill-Herren, 2021).

TCA recognizes that the economy's productive assets extend beyond the assets currently accounted for and include natural, social and human capital (TEEB, 2018; Dasgupta, 2021). A TCA assessment can be done at different levels: a food system, a policy, a region, an organization, an investment or a product (Baker et al., 2020). An overview of the approach and tools available is presented in Annex 1.

A TCA assessment typically starts by identifying the goal and scope of the assessment, establishing the unit of analysis and the system boundaries. Then various externalities are assessed (qualitatively or quantitatively), valued and aggregated (NCC, 2016; TEEB 2018; Impact Institute 2019). It should be noted that the maturity of methods and data to measure, value and attribute externalities varies greatly. The quantification of carbon emissions is relatively mature, whereas the quantification of health externalities is quite young and involves substantial uncertainty (Gemmill-Herren, 2021).

There is limited information available at this scale due to the young nature of TCA, the complexity of food chains and the large variety of disciplines and data required. Although TCA results will never be perfect or entirely objective, TCA provides actors in the food chain with much better information about the value of food than they currently have. However, given the ubiquity of externalities, the complexity of TCA, and the significant interests involved, actors in food systems need an abundant supply of affordable, comparable and reliable TCA information.

Available estimates (FOLU, 2019) approximate the external costs of the global food system due to GHG emissions at 1.5 trillion (2018) USD, other 'natural capital costs' at 1.7 trillion USD and "Pollution, Pesticides & Anti-Microbial Resistance" at 2.1 trillion USD. The 2019 FOLU study estimated health costs due to obesity at 2.7 USD in that study. An exploratory calculation by van Nieuwkoop (2019) estimated the annual external costs of the food system to be at least 6 trillion USD. A study by FAO (2015) estimated the natural capital costs of crop production at around 1.15 trillion USD. The results of other available estimates are presented in Annex 2.

4. REDESIGNING THE ECONOMICS OF FOOD: TRUE PRICING

Once we understand the true cost of food, food system transformation requires a redesign of the economics of food through true pricing - the integration of externalities in prices. An effective redesign of the economics of food based on TCA should address market and policy failures. True pricing addresses market externalities and is an essential complement to other policies such as social protection needed to remedy other market failures. True pricing complements other public policies (such as redistributive systems) by limiting the harm caused by negative externalities. True pricing can incentivize the private sector to provide more beneficial externalities from healthy, sustainable food production and consumption. True pricing can also limit social injustice and address some of the causes of cultural and political conflict. In addition to true pricing, active management by governments of systemic public goods, such as food security, infrastructure, the total stock of biodiversity, and stability, is needed.

A major challenge is putting theory into practice: how to reliably measure, trace and account for externalities

2 A report by the Harvard Business School found that by 2019, at least 56 companies worldwide had disclosed monetized information about their impact, of which five were in the food sector (Serafeim et al., 2019). By 2021, around ten food multinationals are members of the Capitals Coalition (CC, 2021b), and various leading multinational participate in WBCSDs True Value of Food project (WBCSD, 2021b).

throughout the entire value chain of food products. For a long time, this was simply impossible. For more than a century, economists have recognized that the solution to externalities is their internalization in prices (Pigou, 1920; Laffont, 2017). However, in practice, internalizing externalities has been elusive to economists and policy-makers due to the impossibilities of (i) quantifying and pricing externalities, (ii) creating political support for pricing externalities and (iii) measuring and accounting for externalities (Gemmill-Herren, 2021).

However, modern advances in technology have changed this by expanding the options and reducing the costs to store, communicate, validate, and process information (Gemmill-Herren et al., 2021). Recent advances in digital technology, environmental science and economics may allow businesses and governments to apply TCA and true pricing. This presents a major opportunity to support the transition to sustainable food systems. Some of these advances include:

- TCA has provided the science to quantify and price externalities, albeit with uncertainties, as discussed in the previous section.
- Key advances in technologies to measure environmental observables have increased the availability of up-to-date primary data about the effects of economic activity on environmental resources. For example, with satellite technologies, it is possible to monitor deforestation (Finer et al., 2018) or agricultural irrigation water use (Foster et al., 2020) in near real-time.
- Modern sensor technologies, in principle, allow for ubiquitous, low-cost automatic measurement of emissions (Maag et al., 2018).
- The tracing of primary non-financial information across the value chain has been facilitated by widely accessible information technology and can currently be done through identity preservation, segregation, mass balance and book-and-claim traceability systems (Mol & Oosterveer, 2015).
- Distributed ledger technologies have the potential to address both traceability and control by providing in real-time a clear and immutable audit trail for externalities data in a blockchain network shared by all actors in the value chain (Demastichas et al., 2020). Over 50 blockchain studies in agriculture and foods from bananas to salmon and pork are now available. Demastichas et al. (2020) found over twelve commercial solutions in a recent review.
- 'Big data' technologies – primarily leveraging existing scientific and statistical models with more significant memory and computational capacity – are currently being used to estimate externalities (Song et al., 2018), leading to various databases (UNEP, 2020). As primary data is currently still very scarce, developing the technologies and building databases are essential in the near future. Nonetheless, they will require an unprecedented level of international cooperation, including both public and private sectors.

Scientific insight corrects long-standing tenets that pricing externalities reduce purchasing power and that consumers and citizens are not interested in externalities. Citizens and consumers are interested in externalities. Modern research in behavioral economics and consumer science shows that the majority of people are not selfish but have (conditional) pro-social preferences (Fehr & Fischbacher, 2003) and are interested in sustainability, but price plays a foundational consideration in consumption choices (White et al., 2020; PwC, 2020). In addition, recent political science research is uncovering empirical evidence that revenue recycling could lead to majority support for environmental taxation (MacGrath et al., 2019). By better aligning taxation and subsidies with externalities, true pricing can reduce distortionary taxes and make subsidies more efficient (Freire-Gonzalves, 2018).

As a result of the scientific and technological progress, cases of true pricing by market players have emerged in the past years:

- Various food producers, traders and farmers have used it to make their production more sustainable and involve their customers in the price implications (Eosta 2017; Tony's Chocolonely, 2018; True Price 2020c).
- A small number of retailers have used it to provide transparency (Penny's, 2020) about the true price or even charge for it (Time, 2021).
- A fairtrade certifier uses true pricing to improve its value chain (Fairtrade International, 2019).
- Even governments have started to use it. For example, the Dutch Competition Authority allows true pricing as a criterion to justify sustainability collaborations (ACM, 2020).

These cases show that true pricing is possible but represent a small number of early adopters. For true pricing to actually solve the global problem of true costs, it should be implemented at scale throughout global food systems.

Table 2 Pathways for true pricing

Pathway type	Pathway
Market-based	1. The provision of transparency about true prices of products by businesses. 2. The purchase of products with lower true costs due to sustainable consumption. 3. The reduction of true costs by businesses through more sustainable production. 4. The payment of environmental costs by market players to restore damages to natural capital. 5. The respect by businesses of human rights and remediation of breaches where they occur.
Regulatory policies	6. Mandatory transparency of externalities of food products enforced by governments. 7. The incentivization of healthier and more sustainable food through taxes and subsidies by governments to incentivize businesses to produce sustainable products and enable consumers to buy them. 8. The enforcement by governments of the restoration of natural capital and the respect of human rights along the value chain of food products.
Income policies	9. The establishment and enforcement of labor prices (living wages and income) and minimum income (such as a basic income) that guarantee access to healthy and sustainable diets for all. 10. Ensuring an equitable distribution of the collective benefits of true pricing, including savings in public expenditures on healthcare and environmental mitigation.

Various pathways can be identified for its implementation (True Price 2020; Gemmill-Herren, 2021). Market-based pathways can significantly internalize externalities by enabling the expression of pro-social preferences in market choices and creating endogenous market incentives. See Table 2 for some of these pathways. Nonetheless, given the profit motive of businesses, consumers' budgetary constraints and the conditional nature of pro-social preferences, government intervention and international frameworks and agreements are likely required to fully internalize externalities.

Governments can establish 'first-best' true pricing mechanisms, which are welfare-efficient and equitable in the long term. First-best mechanisms would entail an optimal combination of regulatory and income policies. Regulatory policies would have a primary purpose to provide incentives and safeguards for market-based pathways. However, international trade regulations are a constraint to such change. The World Trade Organisation (WTO) rules impose economic competition strictly based on prices and do not consider externalities.

Income policies would ensure that people have sufficient income to buy healthy diets and no significant inequalities arise by the shift in production and consumption patterns. However, current trends in inequalities show this is unlikely without structural changes (transitioning from low productivity and labor-intensive economic activities to higher productivity, sustainable and skill-intensive activities) across all sectors, far beyond changes in food systems only. Moreover, there are numerous factors in current food systems which need to be considered, including agricultural specialization with some regions having converted to cash crop monocultures and others to intensive livestock, large dependencies in the access to modern agriculture. Agroecological systems are more likely to provide diversified food (contributing to healthy diets) with a lower environmental footprint. However, in some cases, organic farms have relatively large emissions of GHGs per unit product. True pricing would need to be deployed with strong policies supporting large structural changes in agriculture.

First-best true pricing mechanisms could support fully sustainable food systems:

- affordable, healthy diets with a small environmental footprint;
- all people participating in the economy would have access to healthy food baskets; and
- human rights would be respected and nature would be conserved.

However, there remain substantial technological and political constraints to implement first-best mechanisms (e.g. OECD, 2006). Applying the first-best true pricing mechanisms also requires:

- building technological infrastructure to collect and trace externalities along the value chain,
- modernizing the implementation of fiscal systems,
- integrating true pricing into international trade agreements and
- creating popular understanding and support for true pricing.

Therefore, governments could adopt pragmatic 'second-best' true pricing policies that take these constraints into account in the short run. Second-best policies effectively incentivize sustainable, healthy and affordable food without imposing significant administrative burdens or complexities. The most suitable mechanism for each country will also be context-dependent and country-specific. Some examples of potential policies that create smart incentives are the following:

- Subsidize healthy and sustainable food products for consumers, financed by eliminating distorting or inefficient subsidies or a carbon tax on carbon emissions by businesses.
- Stimulate true pricing through public procurement, prioritizing foods with low external costs.
- Integrate true pricing in risk and capital regulation by central banks.

A recent study by the World Bank found that agricultural subsidies were 30% of the total agricultural value-added, only 9% of which explicitly supports environmental conservation in OECD and eleven major developing countries (Searchinger et al., 2020). Afshin et al's. (2017) meta-study on studies in high-income countries found that, on average, a 10% decrease in price increased the consumption of healthful foods by 13%. In addition, there is recent evidence that fiscal incentives decrease the amount of cognitive control required to buy healthier food, suggesting it is possible to "titrate the amount of tax reductions and rebates on healthy food items so that they consistently become more preferable than unhealthy foods" (Banerjee et al, 2020). Given that price elasticities are much higher for low-income households and countries (Muhammed et al., 2017; Sassi et al. 2018), the effects of price reductions are expected to be much more extensive for low-income countries and lower-income individuals in advanced economies.

Both the design of pragmatic second-best and optimal first-best true pricing mechanisms need to be informed by data. The findings of the working group's analyses are presented in sections 5 and 6 already as an exploratory illustration of how such mechanisms could work.

5. ESTIMATING THE TRUE COSTS OF FOOD SYSTEMS IN THE CONTEXT OF THE UNFSS ASPIRATIONS

A novel analysis was conducted by a working group of the UNFSS Scientific Group to estimate the true costs of the current food system and estimate the costs of changes towards a more sustainable food system. The work brought together diverse sources of data and approaches. The core unit of analysis was the global food system, consisting of global food consumption and production, divided by country and food group. The environmental and health externalities (listed in Table 3) were estimated based on the externalities for which data were available at this scale and level of granularity. The current analysis excluded economic externalities, social externalities, some environmental externalities (soil degradation, depletion of non-renewable resources, land use other than cropland, overuse of renewable resources and other air pollutants than NH3), and health costs such as antibiotic resistance, zoonoses and undernutrition as well as productivity losses due to disease. Although these are important sources of externalities, time, data availability, data coverage and compatibility limited the inclusion of these costs. In particular, the requirement that data be available per food group excluded many externalities.

The value chain scope for environmental externalities was primary production, feed for animal products, inputs such as nitrogen and phosphate. Transportation, processing and food preparation costs were not considered in the analysis. Previous studies have shown

Table 3 Data included in the study

Type of externality	Externality	Endpoint impact(s)
Environmental	GHG emissions Nitrogen water pollution Phosphorus water pollution Scarce blue water use Land use Air pollution (NH_3)	Contribution to climate change Biodiversity loss Biodiversity loss Depletion of scarce water Biodiversity, ecosystem services Mortality and disability
Health (Human life)	Contribution to cardiovascular diseases Contribution to diabetes mellitus type 2 Contribution to neoplasms (cancers)	Mortality Mortality Mortality
Health (economic costs)	Contribution to cardiovascular diseases Contribution to diabetes mellitus type 2 Contribution to neoplasms	Medical costs, informal care, lost working days Medical costs, informal care, lost working days Medical costs, informal care, lost working days

the vast majority of environmental externalities are in the primary process (FAO, 2015; Baltussen, 2017).

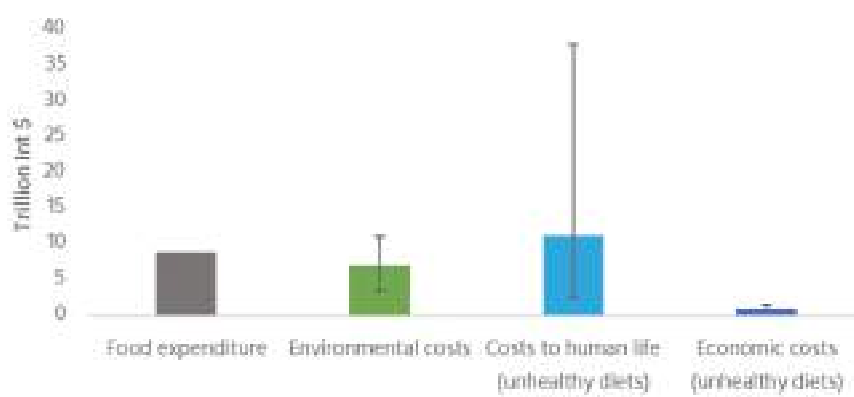
Many data sources and methods were used to quantify the externalities, including Afshin et al. (2019) and Springmann et al. (2018a) to quantify the health impacts and Pozzer et al. (2017), Schipper et al. (2018a), Willet et al. (2019) and WWF (2020) to quantify the environmental impacts. The effects were modeled per food group as set out in Willet et al's. (2019) health reference diet. Consumption per food group was based on expenditure. Production was based on production data per country and food group but is presented here as an aggregate for the world. The environmental effects of imports were based on a global average of the environmental effects of exports per food group.

The monetization of environmental externalities was based on country-level monetization factors for restoration and compensation costs. The methodology adopted has been described by Galgani et al. (2021) and True Price (2020b). A single median global value was used to monetize the loss of human life, based on a meta-study by the OECD (2012) on the value of a statistical life. An average value was used to estimate the direct and indirect economic effects of health loss.

The true annual cost of food was estimated to be around 7 trillion USD (range 4-11) for environmental costs, 11 trillion USD (range 3-39) in costs to human life and 1 trillion USD (range 0.2-1.8) in economic costs (Figure 1). The annual estimate is based on the most recently available data.

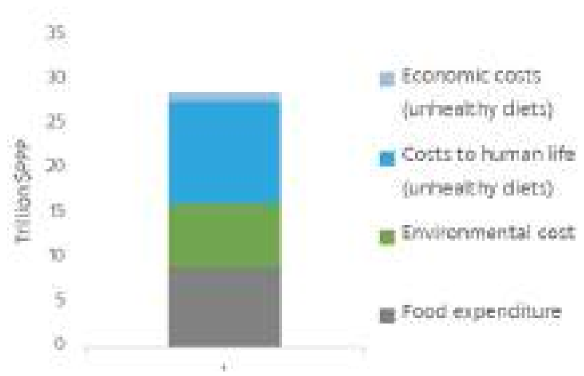
Figure 2 shows that the mean estimate for the total cost of food was 29 trillion USD per year. Given that the current cost of food at current market prices is 9 trillion USD, the results show that the true cost of food is disproportionally high. There is substantial uncertainty in the estimates, particularly for the health costs as impact pathways have not been extensively studied. The counterfactual is not self-evident and externalities relate more to diets than to products. In addition, it should be stressed that this is not a complete picture, as some relevant externalities are not yet included, as indicated above.

Figure 1 The annual true cost of food for the globe



Note: the bar represents the range of possible costs.

Figure 2 Mean estimate of the total annual true cost of food including the external costs in scope of the analysis



Note: This estimate excludes relevant externalities and estimates of included externalities include uncertainty.

Among the highest environmental costs are GHG emissions leading to climate change, land use and land use change leading to loss of ecosystems and biodiversity, and air pollution leading to, among others, loss of biodiversity and human health (Figure 3).

Figure 4 shows the breakdown of the diet-related deaths related to unhealthy food systems, which drives both loss of human life and economic costs of healthcare. The most considerable contribution is due to cardiovascular diseases. Note that the health costs are borne by the current population, whereas a significant part of the environmental costs will be carried by future generations (IPCC, 2014).

These findings align with previous studies in terms of order of magnitude, including those of the FOLU (2019) study. A major methodological difference with the FOLU (2019) outcomes is that the FOLU (2019) study was based on global estimates of the food sector. In contrast, the current analysis is based on a breakdown per country and food group. Van Nieuwkoop's (2019) estimate included fewer impacts and impact pathways than used in this study and intended to provide a first estimate of a lower boundary of the external costs. The current results for land use change align with the FAO (2015) estimate of natural capital costs of crop production (although the scopes are somewhat different).

It should be noted that there is substantial uncertainty in these as well as other existing estimates of the external costs of food, due to (i) an incomplete coverage of impacts, (ii) major uncertainties in primary data, (iii) uncertainties in trade data, (iv) uncertainties in the modeling of impact pathways and (v) uncertainty in the monetization of external costs. An uncertainty range was created for the results based on footprint and valuation uncertainty. Given that not all uncertainties can be captured and not all sources quantify their uncertainty, the ranges should be interpreted comparatively.

Figure 3 Breakdown of the annual environmental cost of food systems

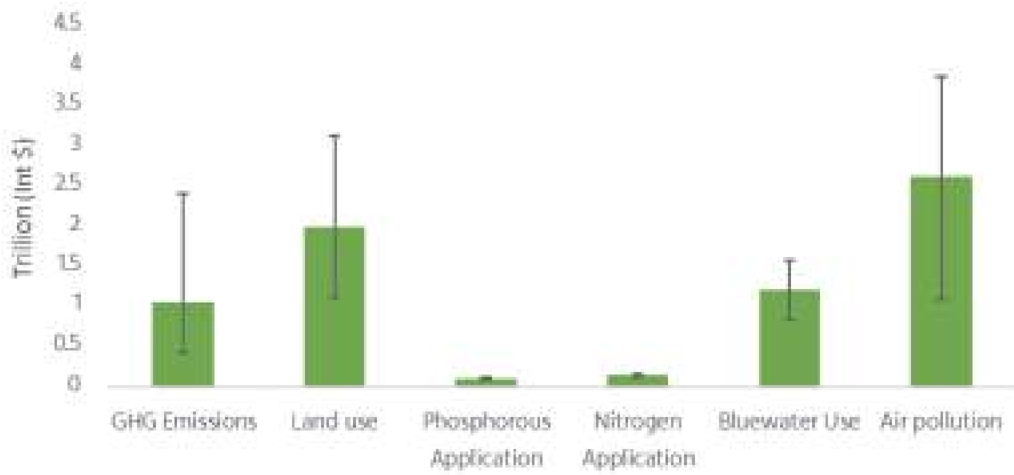
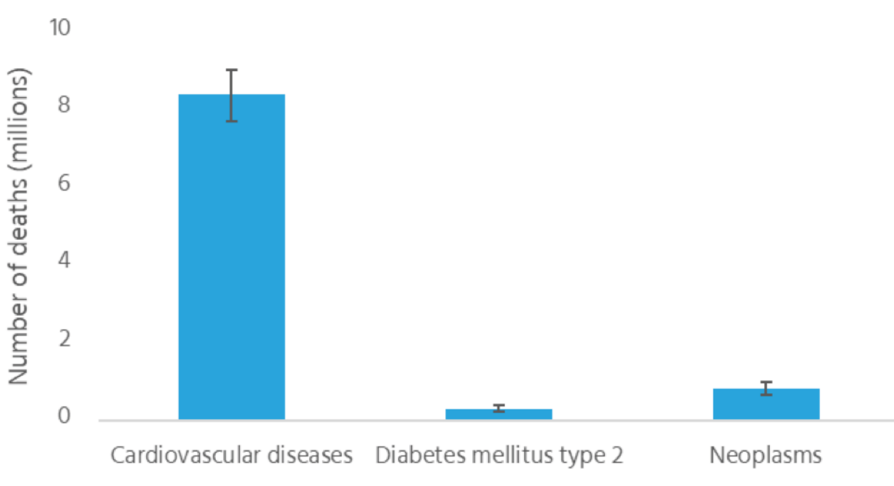


Figure 4 Breakdown of annual diet-related deaths



Environmental impact pathways that have high uncertainty include biodiversity and pollution. Quantifying and valuing the health impacts of diets is a novel field, and methodological choices around attribution, the rationality of consumers, the reference scenario and the valuation of a statistical life affect the estimates. No quantified dietary guide is currently available to support the analysis of achieving the ambitions of the UNFSS. This is an area that requires more attention and quantification.

Further research is required to include relevant externalities related to undernutrition (which ultimately affects human productivity and incomes), zoonoses, antimicrobial resistance (AMR), productivity losses due to diseases, soil degradation, land use other than cropland, and depleted resources. In addition, it is important to add social costs such as underpayment of workers, underearning of farmers, child labor and harassment throughout the value chain.

6. POTENTIAL BENEFITS OF TRANSITIONS TO MORE SUSTAINABLE DIETS

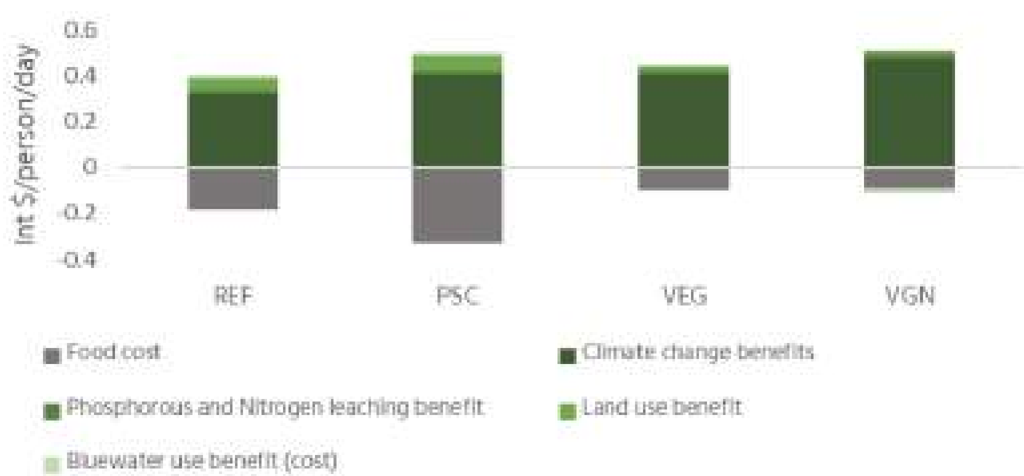
Effective policy interventions to redesign the economics of food also require an understanding of the effects of possible transitions on environmental and health externalities as well as affordability. Such interventions involve realizing multiple goals and making trade-offs, which can be managed by developing well-planned transition pathways, careful monitoring of key indicators, and implementing transparent science targets at the local level (Herrero et al., 2021).

Hence, in addition to estimating current global external environmental and health costs of food, the working group also explored the potential benefits on health and environment of dietary shifts and their implications on affordability. Due to a lack of availability of recent international dietary guidelines, the analysis used the only available EAT-Lancet alternative diets (Springmann et al., 2018). The working group in no way promotes these as recommended diets. The EAT-Lancet's recommended dietary patterns were based on the assumption that plant food production is more environmentally sustainable compared to animal food production, primarily based on considerations of land and water use, energy conversion and greenhouse gas emissions. However, these recommended diets do not consider differences in protein quality and nutrient bioavailability (Moughan, 2021). Nonetheless, the EAT-Lancet pescatarian, vegetarian and vegan diets offer a comparison to a healthy reference diet.

For illustrative purposes, the analysis of shifting consumption patterns to align with these four dietary alternatives showed that significant gains could be achieved in reducing environmental and health costs (Figure 6). However, these shifts do increase the average cost of food, albeit at a small fraction of the gains.

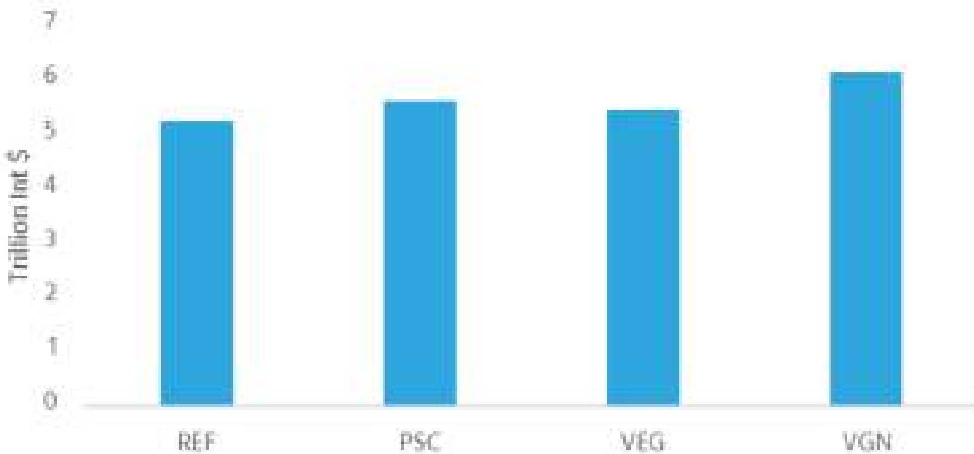
The health benefits of global dietary shifts are potentially substantial (Figure 7). Ensuring the affordability of (healthy) food for all requires detailed analysis about how any interventions affect the poorest groups in society. The current analysis does not cover the distributional effects of dietary shifts. This represents a critical area for future research.

Figure 6 Costs and benefits of potential dietary shifts



REF= Healthy Reference diet, PSC = pescatarian, VEG = vegetarian and VGN = vegan diets.

Figure 7 Health benefits of potential dietary shifts



REF= Healthy Reference diet, PSC = pescatarian, VEG = vegetarian and VGN = vegan diets.

7. STUDY LIMITATIONS

The methodology applied to estimate the true costs of the global food system and alternative diets has the following limitations:

- The environmental cost of dietary shifts did not take household food waste into account. The results were based on dietary guidelines for consumption.
- All scenarios were based on the environmental footprints per kg of product in the current system. Potential reductions in footprints due to a change in cultivation techniques were not taken into account.
- For the land use of animal products, pastureland was not included. The biomes used for growing the feed and the mean species abundance of the land used were determined from global averages of these data for products frequently used as feed (mainly cereal products). For processed food products such as vegetable oils and sugar, the biomes used and the mean species abundance were estimated by averages within the country.
- Air pollution emissions referred to the agricultural sector as a whole, and not only food production.
- The impact of food safety on human health and food waste has not been considered but is a cause of significant disease and mortalities.
- The effect of food production on AMR was not covered in the analysis. According to the AMR review (O'Neill 2016), each year at least 700,000 deaths are caused by AMR, which corresponds to a cost of 2.3 trillion USD using the same valuation approach as for other health impacts in this study. A substantial part of this should be due to food production, but it is currently unclear how much.
- The bioavailability and quality of protein and nutrients were not considered in the dietary shifts but is an important consideration for future research.

8. TOWARDS SCIENCE-BASED AND PRAGMATIC TRUE PRICING MECHANISMS

In a fully sustainable food system, all people can afford healthy and sustainable food. If the damage to nature is paid for and restored in a sustainable food system, food production costs will increase. Internalizing the environmental costs would significantly reduce the environmental footprint by providing an incentive to avoid or reduce such costs in the first place, albeit at a cost to producers. A corrected price mechanism may nudge producers and processors to produce food in a more sustainable way to the benefit of the producers themselves. Those stakeholders that are already more sustainably producing healthy foods will have a comparative competitive advantage.

In addition, paying minimum wages and ensuring adequate incomes for all workers in the food value chain would further increase the cost of food. At the same time, the realized benefits in human lives would be around 5 trillion USD and the economic savings, mainly through public health care expenditures, around 0.5 trillion USD. With true pricing, substantial savings in public expenditure can be realized through lower health care costs, avoided environmental mitigation measures (such as climate change) and the reduction of subsidies. These savings could be sufficient to make food cheaper than it is now, even after environmental and social costs are internalized, although further research is required.

There are currently substantial constraints to realizing the first-best true pricing mechanisms (see Table 2). More fundamental and applied research must include all aspects of externalities and generate appropriate data to do these analyses. Therefore, efforts should focus on supporting market-based pathways and pragmatic second-best true pricing policies in the short term. These policies effectively incentivize sustainable, healthy and affordable food without imposing enormous administrative burdens or complexities. Nonetheless, they also need to support structural changes in agriculture, food industries and international trade.

Suppose governments would like to incentivize a transition to the reference diet analyzed in 5 and 6 to reap the environmental and health benefits. In this case, the reference diet would, on average, be 6% more expensive than the current global consumption pattern and less affordable for many. A second-best true pricing mechanism could focus on making this diet 10% cheaper. In global terms, this would cost at most 1 trillion USD. This could, for example, be financed by a carbon tax on businesses or partly funded by reducing existing inefficient or less efficient subsidies.

Such a policy change may not cost taxpayers anything while making healthy diets more affordable and contributing to the achievement of the Paris agreement. Depending on the success in shifting dietary patterns, the shift could reduce the environmental costs of the food sector by 0.1- 1 trillion USD per year and create health savings of 0.7-5 trillion USD. It should be noted that these are speculative estimates and further research should explicitly model behavioral, market and ecological effects and interactions. In addition, any policy should be focused on country-level data. Nonetheless, substantial benefits can be realized with a relatively simple intervention that (i) does not require measuring all externalities of food products in the short run and (ii) would presumably be popular as it reduces the price of healthy food.

9. RECOMMENDATIONS

Given the high costs to the environment and human health presented in these findings, it is essential that UNFSS stakeholders actively identify externalities that represent 'hidden costs' in the food system and those that ignore or incentivize unsustainable and unhealthy food systems. These costs need to be quantified through TCA practices and pathways identified to reduce or eliminate these externalities through policies that: (i) internalize externalities and (ii) sanction those food system stakeholders who do not take appropriate steps to reduce and internalize these costs and/or incentivize those who do. Estimating the full scope of these costs is a priority to determine if such an adjustment to the food system would increase food prices to a point where a reassessment of poverty lines is necessary to ensure access to healthy diets for the poorest.

In the short term, policy-makers can remove the barriers for stakeholders to engage in TCA and use TCA data to redefine the value of food to reflect its true costs and benefits. In particular, governments and other UNFSS stakeholders can:

- **Foster internationally accepted harmonized TCA principles across all applications.** Together experts, practitioners and stakeholders from all fields in food and agriculture harmonized TCA principles can be developed to ensure validity and comparability of results and alignment between the various levels.
- **Educate and build capacity among professionals in business and government about TCA.** Build the new discipline of TCA it is important. Harmonized principles are necessary to bring experts and practitioners from all fields together. In addition, TCA can be integrated into educational systems and current food professionals in government, civil society and business can be educated in TCA.
- **Provide professionals in business and governments with concrete tools to facilitate TCA.** Lowering the entry barriers of professionals to the complex field of TCA can be facilitated by providing practical skills and approaches (toolboxes) for analysis.

In the medium and long term, governments can look at ways to integrate TCA in economic metrics at all levels systematically:

- **Integrate TCA into National Accounts and GDP.** This can provide a standardized account of how much inclusive welfare (realized welfare and changes in wealth) was created. This would provide a much better view of how the food sector contributes to welfare.
- **Integrate TCA into business sustainability reporting and controls.** By adding TCA information into their internal and external financial reports, businesses can compile impact-weighted accounts and impact statements, enabling them to report and manage the value they create to all stakeholders via all capitals.
- **Integrate TCA into product labeling.** Products can show their true costs to their customers (in monetized terms), as well as their true value (in monetized terms or otherwise).

In the short term, policy-makers could redesign the economics of food via true pricing by focusing on:

- **Supporting market players to engage in true pricing, enabling** the expression of preferences for sustainable and healthy food into choices, and creating endogenous market incentives
- **Pursuing pragmatic second-best true pricing approaches** that create smart incentives that significantly correct the price signal without increasing food prices or imposing high administrative costs.

Governments and other stakeholders of the UNFSS could enable both market-based and second-best government-led true pricing pathways, policy-makers and other food stakeholders can work together to:

- **Establish an international measurement standard for true pricing** based on a scientific consensus process and in alignment with governments and stakeholders.
- **Develop a global true pricing** database with the true prices and true costs of food products consolidating existing scientific knowledge, providing reference values and benchmarks for the most important externalities for each agricultural and food product and each country.
- **Support SMEs and smallholder farmers** who want to sell their products at a true price to businesses and consumers.
- **Create a policy toolbox for governments** to implement short term true pricing policies based on feasibility and impact studies of various second-best true pricing policies.
- **Create a modeling toolbox** to estimate the effects of short term true pricing policies on the environment, health and affordability.

Finally, policy-makers can start to explore how first-best mechanisms for the medium term:

- **Develop science-based first-best true pricing** mechanisms based on integrated TCA assessments of the food system and sustainable mechanism design.
- **Generate a global agreement and create public-private partnerships around a roadmap to realize the SDGs by 2030 and reach fully sustainable food systems by 2050** with affordable and healthy food without environmental, social and health costs.
- **Create a technological alliance to Invest in affordable, traceable, sustainable, reliable and fair technologies to allow all market players, big and small, to implement true pricing in practice.** This includes technology, science and inclusive governance to (i) measure primary environmental, health and social impacts and (ii) reliably trace and account for the true price of food products along the entire value chain.

REFERENCES

1. ACM (2020). Guidelines Sustainability Agreements. Available at https://www.acm.nl/en/publications/draft-guidelines-sustainability-agreements.
2. Addy et al. (2019) Calculating the Value of Impact Investing: An evidence-based way to estimate social and environmental returns. Harvard Business Review, January – February 2019. Available at https://hbr.org/2019/01/calculating-the-value-of-impact-investing.
3. Afshin A. et al. (2017) The prospective impact of food pricing on improving dietary consumption: A systematic review and meta-analysis. PLoS ONE, 12, 3, e0172277.
4. Afshin, A., et al. (2019). Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet, 393(10184), 1958-1972.
5. Allen, T., & Prosperi, P. (2016). Modeling sustainable food systems. Environmental management, 57(5), 956-975. https://doi.org/10.1007/s00267-016-0664-8.
6. Baker, L., Castilleja, G., De Groot Ruiz, A. & Jones A. (2020). Prospects for the true cost accounting of food systems. Nat Food 1, 765–767 (2020). Available at https://doi.org/10.1038/s43016-020-00193-6.
7. Baltussen, W., van Berkum, S., Dijkxhoorn, Y., Helmes, R.,ÖzkanGülzari, Ş,Vellinga, T., Massawe, G.D.,Galgani, P.,Borniotto, D.,van den Elzen, F. and Smith,T. (2019), Traditional livestock systems in Tanzania; An application of the TEEBAgriFood EvaluationFramework. TEEBfor Agriculture and Food, UNEP.
8. Baltussen, W., Achterbosch, T., Arets, E., de Blaeij, A., Erlenborn, N., Fobelets, V., Galgani, P., de Groot, R. A., Hardwicke, R., Hiemstra, S. J., van Horne, P., Karachalios, O. A., Kruseman, G., Lord, R., Ouweltjes, W., Tarin, R. M., Vellinga, T., & Verkooijen, L. (2016). Valuation of livestock eco-agri-food systems: poultry, beef and dairy : executive summary. Wageningen Economic Research report; No. 2016-023. https://doi.org/10.18174/389545.
9. Banerjee, T., Chattaraman, V., Zou, H. et al. (2020). A neurobehavioral study on the efficacy of price interventions in promoting healthy food choices among low socioeconomic families. Sci Rep 10, 15435. https://doi.org/10.1038/s41598-020-71082-y.
10. Beiser-McGrath, L.M., & Bernauer, T. Could revenue recycling make effective carbon taxation politically feasible? Sci. Adv., 5, eaax3323 (2019).
11. Bowles, S. & Carlin, W. (2020). Inequality as experienced difference: A reformulation of the Gini coefficient. Economics Letters, 186, 108789. https://www.sciencedirect.com/science/article/pii/S0165176519303969.
12. Buchanan, J. M., & Stubblebine, W. C. (1962). Externality. In Classic papers in natural resource economics (pp. 138-154). Palgrave Macmillan, London.
13. Capitals Coalition (2021a). Principles of integrated capitals assessments. Available at: https://capitalscoalition.org/wp-content/uploads/2021/01/Principles_of_integrated_capitals_assessments_final.pdf.
14. Capitals Coalition (2021b). Capitals Coalition. Organization directory. Available at: https://capitalscoalition.org/the-coalition/ Accessed: 10 May 2021.
15. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. Science, 361(6407), 1108-1111. https://doi.org/10.1126/science.aau3445.
16. Dalin, C., & Outhwaite, C. L. (2019). Impacts of global food systems on biodiversity and water: the vision of two reports and future aims. One Earth, 1(3), 298-302. https://doi.org/10.1016/j.oneear.2019.10.01.
17. Darrah, S. E., Shennan-Farpón, Y., Loh, J., Davidson, N. C., Finlayson, C. M., Gardner, R. C., & Matt, W. J. (2019). Improvements to the Wetland Extent Trends (WET) index as a tool for monitoring natural and human-made wetlands. Ecological Indicators, 99, 294-298. https://doi.org/10.1016/j.ecolind.2018.12.032.
18. Dasgupta, Manuga and Kumar (2021). The inclusive wealth index and sustainable development goals. Sustainability Science. Available at https://link.springer.com/article/10.1007/s11625-021-00915-0.
19. Demastichas K. et al. Blockchain in Agriculture Traceability Systems: A Review. Appl. Sci., 10, 4113 (2020). doi:10.3390/app1012411.
20. Dore, M.H.I & Burton, I. (2003). Environmental degradation and remediation: Is economics part of the problem. Environmental Monitoring and Assessment, 86, 47–61.
21. Eosta, Soil & More, EY, Triodos Bank, Hivos (2017) True Cost Accounting for Food, Farming & Finance. Available at https://truepricefoundation.sharepoint.com/sites/TruePriceCoreGroup/Shared%20Documents/9.%20External%20Shared%20Folders/UNFSS%20Scientific%20Group%20Shared/1.%09https:/www.natureandmore.com/files/documenten/tca-fff-report.pdf.
22. Faitrade International (2019) The external costs of banana production: A global study. Response from the commissioning agency, Fairtrade Inter-

national. Available at https://truepricefoundation.sharepoint.com/sites/TruePriceCoreGroup/Shared%20Documents/9.%20External%20Shared%20Folders/UNFSS%20Scientific%20Group%20Shared/1.%09https:/files.fairtrade.net/publications/2018_CostsBananaProduction_ManagementResponse.pdf.
23. FAO (2014). Food wastage footprint: full-cost accounting. FAO, Rome. Food Wastage Footprint: Fool cost-accounting (fao.org).
24. FAO (2015). Natural Capital Impacts in Agriculture. Supporting better business decision making. http://www.fao.org/fileadmin/templates/nr/sustainability_pathways/docs/Natural_Capital_Impacts_in_Agriculture_final.pdf.
25. FAO, IFAD, UNICEF, WFP and WHO. (2020). The State of Food Security and Nutrition in the World 2020. Rome: FAO.
26. FAO, IFAD, UNICEF, WFP, & WHO. (2020). The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Food and Agriculture Organisation of the United Nations, Rome, FAO. https://doi.org/10.4060/ca9692en.
27. Fehr, E. & Fischbacher, U. The nature of human altruism. Nature, 425, 785–791 (2003). doi:10.1038/nature02043.
28. Finer, M. et al. (2018). Combating deforestation: From satellite to intervention. Science, 360, 6395, 1303-1305.
29. FOLU (Food and Land Use Coalition). (2019), Growing Better: Ten Critical Transitions to Transform Food and Land Use, The Global Consultation Report of the Food and Land Use Coalition, https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf.
30. Food and Land Use Coalition (2019). Growing Better: Ten Critical Transitions to Transform Food and Land Use. Available at https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf.
31. Foster, T., Mieno, T., & Brozovic, N.(2020). Satellite-based monitoring of irrigation water use: Assessing measurement errors and their implications for agricultural water management policy. Water Resources Research, 56, e2020WR028378. https://doi.org/10.1029/2020WR028378.
32. Freire-González, J. Environmental taxation and the double dividend hypothesis in CGE modelling literature: A critical review. Journal of Policy Modeling, 40, 194–223 (2018).
33. Gemmill-Herren, B., Baker, L.E., Daniels, P.A., eds. (2021 Forthcoming). True Cost Accounting for Food Balancing the Scale. Routledge.
34. Global LCA Data Access. Life Cycle Initiative. (UN Environment Program, 2020-2021). https://www.globallcadataaccess.org/.
35. Gowdy D. & Erickson J.D. (2005). The approach of ecological economics. Cambridge Journal of Economics, 29, 207–222 doi:10.1093/cje/bei033.
36. Gruber J, & Köszegi B (2001). Is addiction "rational"? Theory and evidence. The Quarterly Journal of Economics, 116(4), 1261–1303.
37. Hauschild, M.Z., Rosenbaum, R.K. & Olsen, S.I. (2018). Life Cycle Assessment: Theory and Practice. Springer, Cham.
38. Haws, K.L, Walker Reczek, R., Sample, K.L. (2017). Healthy Diets Make Empty Wallets: The Healthy = Expensive Intuition. Journal of Consumer Research, 43, 6, 992–1007. https://doi.org/10.1093/jcr/ucw078.
39. Herrero, M., et al. (2021). Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health, 5 (1), e50 - e62.
40. Herrero, M., Thornton, P. K., Power, B., Bogard, J. R., Remans, R., Fritz, S., et al. (2017). Farming and the geography of nutrient production for human use: A transdisciplinary analysis. The Lancet Planetary Health, 1(1), e33-e42.
41. HLPE, 2011. Price volatility and food security. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2011.
42. Hoekstra, R. (2019). Replacing GDP by 2030: Towards a Common Language for the Well-being and Sustainability Community. Cambridge Univerity Press, Cambridge.
43. Huertas-Valdivia, I. et al. Social Life-Cycle Assessment: A Review by Bibliometric Analysis. Sustainability, 12, 6211 (2020). doi:10.3390/su12156211.
44. Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M. D. M., ... & Van Zelm, R. (2016). ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess (2017) 22:138–147. DOI 10.1007/s11367-016-1246-y.
45. IDH, True Price (2016a). The True Price of Cocoa from Ivory Coast. Available at: https://trueprice.org/wp-content/uploads/2016/03/TP-Cocoa.pdf.
46. IDH, True Price (2016b). The True Price of Tea from Kenya. Available at: https://trueprice.org/wp-content/uploads/2016/04/TP-Tea.pdf.
47. IDH, True Price (2016c). The True Price of Coffee from Vietnam. Available at: https://trueprice.org/wp-content/uploads/2016/04/TP-Coffee.pdf.
48. IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
49. IPPC (2019). Climate change and land, an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, IPPC, www.ipcc.ch/report/srcc.
50. Jaffee, S., Spenser, H., Unnevehr, L., Grace, D., & Cassou, E. (2019). The Safe Food Imperative: Accelerating Progress in Low- and Middle-Income Countries. The World Bank, Washington, DC.
51. Jones, A.(2020). The Sustainable Food Trust pushing forward with pilot framework for sustainability metrics. Sustainable Food Trust (3 April 2020). Available at: https://sustainablefoodtrust.org/articles/the-sustainable-food-trust-pushing-forward-with-pilot-framework-for-sustainability-metrics/.
52. Laffont, J.J. (2008). Externalities. In The New Palgrave Dictionary of Economics. London: Palgrave Macmillan. Available at https://doi.org/10.1057/978-1-349-95121-5_126-2.
53. Lord, S. (2020). Valuing the impact of food: Towards practical and comparable monetary valuation of food system impacts. FoodSIVI. Available at: https://foodsivi.org/wp-content/uploads/2020/06/Valuing-the-impact-of-food-Report_Foodsivi.pdf.
54. Maag, B., Zhou, Z. & Thiele, L. (2018).A survey on sensor calibration in air pollution monitoring deployments. IEEE Internet of Things Journal, 20, 10.
55. Malik, A. et al. (2018). Advancements in Input-Output Models and Indicators for Consumption-Based Accounting. Journal of Industrial Ecology, 23, 2.
56. Marchetti, L., Cattivelli, V., Cocozza, C., Salbitano, F., & Marchetti, M. (2020). Beyond sustainability in food systems: Perspectives from agroecology and social innovation. Sustainability, 12(18), 7524. https://doi.org/10.3390/su12187524.
57. Masters, W.A., Martinez, E.M., Greb, F., Herforth, A, Hendriks, SL. (2021). Cost and Affordability of Preparing a Basic Meal around the World. UN Food Systems Summit Brief Prepared by Research Partners of the Scientific Group for the Food Systems Summit. https://sc-fss2021.org/wp-content/uploads/2021/05/FSS_Brief_Cost_of_Basic_Meals.pdf.
58. McCauley, D.J. (2006). Selling out on Nature. Nature, 443, 27-28.
59. Mol, P.J. & Oosterveer P. Certification of Markets, Markets of Certificates: Tracing Sustainability in Global Agro-Food Value Chains. Sustainability, 7, 12258-12278 (2015). doi:10.3390/su70912258.
60. Moughan, PJ. (2021). Population protein intakes and food sustainability indices: The metrics matter. Global Food Security,29,100548. https://doi.org/10.1016/j.gfs.2021.100548.
61. Muhammad A, D'Souza A, Meade B, et al. (2017). How income and food prices influence global dietary intakes by age and sex: evidence from 164 countries BMJ Global Health;2:e000184. https://gh.bmj.com/content/2/3/e000184.
62. Nakamura S. & Nansai K. (2016). Input–Output and Hybrid LCA. In: Finkbeiner M. (ed) Special Types of Life Cycle Assessment. LCA Compendium – The Complete World of Life Cycle Assessment. Springer https://doi.org/10.1007/978-94-017-7610-3_6
63. Natural Capital Coalition (2016). Natural Capital Protocol. https://capitalscoalition.org/capitals-approach/natural-capital-protocol/?fwp_filter_tabs=guide_supplement.
64. Nkonya, E. Mirzabaev, A., von Braun, J. 2016. Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. https://link.springer.com/book/10.1007/978-3-319-19168-3.
65. OECD (2001). Glossary of statistical terms. Gross Value Added. Available at https://stats.oecd.org/glossary/detail.asp?ID=3215.
66. OECD (2002) Glossary of Statistical Terms. Profit. https://stats.oecd.org/glossary/detail.asp?ID=3288
67. OECD (2003). Glossary of statistical terms. Externalities. Available at https://stats.oecd.org/glossary/detail.asp?ID=3215.
68. Olsen, S. (2020). Impact Monetisation. Impact Management Project. Available at https://impactmanagementproject.com/wp-content/uploads/IMP_Impact-monetisation-discussion-document.pdf.
69. Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., & Wood, R. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. Global Environmental Change, 56, 1-10.
70. Penny (2020) Penny Labels its first products with true prices. Available at https://www.rewe-group.com/en/press-and-media/newsroom/press-releases/penny-labels-its-first-products-with-true-prices/.
71. Pigou, A.C. (2019). The Economics of Welfare. London: Macmillan.
72. Pozzer, A. et al. (2017). Impact of agricultural emission reductions on fine-particulate matter and public health. Atmos. Chem. Phys., 17, 12813–12826, 2017. Available at https://doi.org/10.5194/acp-17-12813-2017.
73. PwC (2019) Global Consumer Insights Survey Sustainability. Retrieved October 11, 2020. Available at: www.pwc.nl/en/insights-and-publications/

services-and-industries/retail-and-consumer-goods/2019-consumer-insights-survey/sustainability.html.

74. Rockstrom, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, III, E. Lambin, T. M. et al. (2009). Planetary boundaries: Exploring the safe operating space for humanity. Ecology and Society 14(2): 32. URL:http://www.ecologyandsociety.org/vol14/iss2/art32/.
75. Sassi, F., Belloni, A., Mirelman, A. J., Suhrcke, M., Thomas, A., Salti, N., Vellakkal, S., Visaruthvong, C., Popkin, B. M., & Nugent, R. (2018). Equity impacts of price policies to promote healthy behaviours. Lancet, 391(10134), 2059–2070. https://doi.org/10.1016/S0140-6736(18)30531-2.
76. Schipper, A.M., Hilbers, J.P., Meijer, J.R., Antão, L.H., Benítez-López, A., de Jonge, M.M., Leemans, L.H., Scheper, E., Alkemade, R., Doelman, J.C. and Mylius, S., 2020. Projecting terrestrial biodiversity intactness with GLOBIO 4. Global Change Biology, 26(2), pp.760-771.
77. Schramade, W. (2020). ABN AMRO's Impact Statements: A Case Study on Making Societal Value Visible. Available at: https://www.rsm.nl/fileadmin/Images_NEW/Erasmus_Platform_for_Sustainable_Value_Creation/Case_study_ABN_AMRO_Schramade.pdf.
78. Searchinger et al. (2020) Revising Public Agricultural Support to Mitigate Climate Change. IBRD/World Bank
79. Serafeim and Trin (2020). Preliminary Framework for Product Impact Weighted Accounts. Harvard Business Schoo. Available at: https://www.hbs.edu/impact-weighted-accounts/Documents/Preliminary-Framework-for-Product-Impact-Weighted-Accounts.pdf.
80. Serafeim, G., Zochowski, T. R. and Downing, J. (2019) Impact-Weighted Financial Accounts: The Missing Piece for an Impact Economy. Harvard Business School. Available at https://www.hbs.edu/impact-weighted-accounts/Documents/579%20Impact-Weighted-Accounts-Report-2019_preview.pdf.
81. Song, M.L., et al. (2018). Environmental performance evaluation with big data: theories and methods. Annals of Operations Research, 270, 459–472 (2018).
82. Springmann, M. (2020). Valuation of health and climate-related benefits of healthy diets. FAO Agricultural Development Economics Working Papers. Background paper for The State of Food Security and Nutrition in the World 2020, 20-03. Rome, FAO.
83. Springmann M, Spajic L, Clark M A, Poore J, Herforth A, Webb P et al. (2020). The healthiness and sustainability of national and global food based dietary guidelines: modelling study BMJ; 370:m2322 doi:10.1136/bmj.m2322.
84. Springmann, M., et al. (2018a). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. The Lancet, 2(10):e451-e461. Available at https://doi.org/10.1016/S2542-5196(18)30206-7.
85. Springmann et al. (2018b). Options for keeping the food system within environmental limits. Nature, 562(7728), 519–525. Available at https://doi.org/10.1038/s41586-018-0594-0.
86. http://www.fao.org/documents/card/en/c/cb1699en/
87. Springmann, M., Godfray HC., Rayner, M., Scarborough, P. (2016). Analysis and valuation of the health and climate change co-benefits of dietary change. Proc Natl Acad Sci, 113: pp. 4146-4151.
88. Stiglitz, J., J. Fitoussi and M. Durand (2018), Beyond GDP: Measuring What Counts for Economic and Social Performance, OECD Publishing, Paris, https://doi.org/10.1787/9789264307292-en.
89. Stuckler D, McKee M, Ebrahim S, Basu S (2012) Manufacturing Epidemics: The Role of Global Producers in Increased Consumption of Unhealthy Commodities Including Processed Foods, Alcohol, and Tobacco. PLoS Med 9(6): e1001235. https://doi.org/10.1371/journal.pmed.1001235.
90. The Economics of Ecosystems and Biodiversity (TEEB) (2018). TEEB for Agriculture & Food: Scientific and Economic Foundations. Geneva: UN Environment.
91. Time Magazine (2021). Amsterdam Is Embracing a Radical New Economic Theory to Help Save the Environment. Could It Also Replace Capitalism? Available at: https://time.com/5930093/amsterdam-doughnut-economics/.
92. Tony's Chocolonely and True Price (2018). The True Cost of Cocoa. Tony's Chocolonely 2018 progress report. Available at https://trueprice.org/wp-content/uploads/2018/11/The-True-Price-of-Cocoa.-Progress-Tonys-Chocolonely-2018.pdf.
93. True Price (2020a), Principles for True Pricing. Amsterdam, The Netherlands. Available at https://trueprice.org/principles-for-true-pricing/.
94. True Price (2020b), Monetisation factors for True Pricing. Amsterdam, The Netherlands. Available at https://trueprice.org/monetisation-factors-for-true-pricing/.
95. True Price (2020c). The true price of Apples. Available at: https://trueprice.org/the-true-price-of-dutch-apples/.
96. UN (2021). System of Environmental Economic Accounting. Available at: https://seea.un.org/.

97. United Nations (1972). Declaration of the United Nations Conference on the Human Environment. Stockholm. Available at: https://www.un.org/ga/search/view_doc.asp?symbol=A/CONF.48/14/REV.1.
98. United Nations (2021). System of Environmental Economic Accounting. Available at https://seea.un.org/ .
99. Van Nieuwkoop (2019). Do the costs of the global food system outweigh its monetary value? World Bank Blogs. June 17, 2019. Available at: https://blogs.worldbank.org/voices/do-costs-global-food-system-outweigh-its-monetary-value. Accessed: May 10, 2021.
100. van Nieuwkoop, M. (2019, June 17). Do the costs of the global food system outweigh its monetary value? World Bank Blogs. Retrieved April 8, 2021, from https://blogs.worldbank.org/voices/do-costs-global-food-system-outweigh-its-monetary-value.
101. Van Praag, M.S. (1991). Ordinal and cardinal utility: An integration of the two dimensions of the welfare concept. Journal of Econometrics, 50, 1–2, 69-89.
102. VBA (2021). VBA METHODOLOGY V0.1 Impact statement. Available at: https://www.value-balancing.com/_Resources/Persistent/2/6/e/6/26e6d344f3bfa26825244ccfa4a9743f8299e7cf/20210210_VBA%20Impact%20Statement_GeneralPaper.pdf.
103. Wang, Y., & Sloan, F. A. (2018). Present bias and health. Journal of Risk and Uncertainty, 57(2), 177–198. https://doi.org/10.1007/s11166-018-9289-z
104. WBCSD (2018) Social and Human Capital protocol. Available at: https://www.wbcsd.org/Programs/Redefining-Value/Business-Decision-Making/Assess-and-Manage-Performance/Social-Human-Capital-Protocol.
105. WBCSD (2021a). Vision 2050. Pathway Food. Available at https://timetotransform.biz/wp-content/uploads/2021/03/WBSCD_Vision2050_Pathway-Food.pdf.
106. WBCSD (2021b). True True Value of Food. 2021. https://www.wbcsd.org/Programs/Food-and-Nature/Resources/The-True-Value-of-Food. Accessed at: May 10, 2021
107. Westhoek, H., Ingram, J., van Berkum, S., Özay, L., & Hajer, M. (2016). Food Systems and Natural Resources. United Nations Environment Programme. https://www.resourcepanel.org/reports/food-systems-and-natural-resources.
108. White, K., Habib R. & Dahl D.W. (2020). A Review and Framework for Thinking about the Drivers of Prosocial Consumer Behavior. Journal of the Association for Consumer Research, 5, 1, 1-17 .
109. Willet et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet, 6736(18), 3–49. https://doi.org/10.1016/S0140-6736(18)31788-4.
110. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, et al. (2019). Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet, 393(10170):447-492. doi: 10.1016/S0140-6736(18)31788-4.
111. Woolverton, A. and Dimitri, C. (2010). Green marketing: Are environmental and social objectives compatible with profit maximization? Renewable Agriculture and Food Systems: 25(2); 90–98. https://pubag.nal.usda.gov/download/42917/PDF.
112. WWF. (2020). Country comparison – factors v5.0. Available at https://waterriskfilter.panda.org/en/Explore/CountryProfiles#compare/1/2.

ANNEX 1: HOW DOES TRUE COST ACCOUNTING WORK?

A TCA assessment can be done at different levels: a food system, a policy, a region, an organization, an investment or a product (Baker et al, 2020). For each type of analysis, various frameworks exist. A major system-level framework is TEEB for Agriculture and Food (TEEB, 2018). Recently Lord (2020) also published a methodology for food systems analysis. These frameworks can be applied at other levels. At the regional level, the UN System of Environmental-Economic Accounting provides a mature framework for natural capital valuation (SEEA, 2021). For other aspects, few well-accepted frameworks exist (Hoekstra, 2019), although inclusive wealth is a promising approach (Dasgupta et al, 2021b). Various TCA frameworks are being developed for the organizational level, often focusing on corporate reporting (Natural Capital Coalition, 2015; Value Balancing Alliance 2021; Impact Institute, 2019; HBS, 2020). Also, frameworks have been developed specifically for products such as coffee and bananas (True Price, 2020; Serafeim and Trinh, 2020; Galgani et al 2021) and investments (Addy et al, 2019; Olsen, 2020; Impact Institute, 2020).

A TCA assessment starts by defining the goal, scope and unit of analysis ('functional unit'). Consequently, the relevant externalities have to be identified. Once these externalities have been identified, they have to be assessed, qualitatively or quantitatively. Quantification starts with measuring or assessing inputs and outputs, the direct measurable effects of production and consumption (Impact Institute, 2020). These inputs and outputs can be measured using primary data. In practice, inputs and outputs often have to be estimated with macro-level models through (environmentally) Extended Input-Output and Computable General Equilibrium models (Malik et al., 2018), micro-level models such as Life-cycle accounting (LCA) (Hausschilds et al., 2018) and social LCA (Huertas-Valdivia, 2020), or through hybrid approaches (Nakamura & Nansei, 2018). Consequently, these outputs have to be translated to impacts via impact pathways (Impact Institute, 2019).

For many environmental externalities these there are databases for such pathways such as those based on Recipe (Huijbregts et al, 2016), although pathways for ecosystem and biodiversity are more complex (TEEB 2018, Dasgupta, 2021). Impact pathways for social and in particular health externalities are less mature. If the functional unit is a product, investment or organization, the final quantification step is the attribution of impact to the functional unit (Capitals Coalition, 2021; Impact Institute, 2020; VBA, 2021). This process yields quantified impacts in natural units such as CO2 equivalents, liters of scarce blue water extraction or loss Mean Species abundance for environmental externalities, full-time equivalents (FTE) of child labor, FTE of forced labor and underpayment for social externalities, and disability adjusted life years (years of life lost + years lived with a disability) for health externalities (True Price; 2020).

After externalities have been quantified, they can be valued, in monetary terms or otherwise, so that they are expressed in a common unit. To capture value not reflected in market prices, a TCA assessment requires an (implicit or explicit) measure of welfare. Although terminology differs widely in the literature, there is a wide recognition that multiple dimensions exist (Stiglitz et al., 2018) and common welfare dimensions include:

- The preference satisfaction or well-being of people (Stiglitz et al., 2018; TEEB, 2018; Dasgupta, 2021; Impact Institute, 2020).
- An equitable distribution of income and other resources (Stiglitz et al., 2018).
- Adherence to social limits such as a living wage, labor standards and the right to food security, which can be derived from human rights. (TEEB 2018; True Price 2020).
- Adherence to environmental limits, such as the conservation of climate, abiotic resources and biodiversity. These limits can be derived from planetary boundaries for a livable planet (Rockstrom et al, 2009; Stiglitz et al., 2018), the intrinsic value of nature (TEEB, 2018) and/or the rights current and future generations (True Price, 2020).

The first dimension generally coincides with traditional measures of ordinal or cardinal utility economists have used to measure collective welfare (Van Praag 1991; Galgani et al 2021). The second dimension is linked to traditional measures of income inequality such as the GINI coefficient (Bowles & Carlin, 2020). Nonetheless, these measures cannot accommodate central issues in sustainability, such as biophysical limits, human rights, social equity and intergenerational equity (Dore & Burton, 2003; Gowdy & Erickson, 2005). Hence, the valuation of environmental and social damages has met with resistance from non-economists, policy makers and civil society (McCauley, 2006). As a result, in TCA, additional welfare dimensions emerged (Stiglitz et al., 2018; TEEB, 2018; Impact Institute, 2020). Depending on the welfare dimension, different valuation methods, such as cardinal utility, abatement costs, shadow pricing or remediation costs are used (Galgani 2021). A relevant discussion point is to which degree externalities can be summed and netted. Economists would traditionally sum all positive and negative externalities into one number, whereas some TCA frameworks hold that welfare dimensions ought to be considered separately (Stiglitz et al., 2018; Impact Institute, 2019) and human rights violations or deforestation cannot be offset by an equal amount of profit for example (Capitals Coalition, 2021; True Price, 2020).

ANNEX 2: SUMMARY OF ESTIMATES OF PREVIOUS STUDIES FOR EXTERNALITIES AND FOOD SYSTEMS CHANGES

Problem	Estimated costs of current externalities	Estimates of magnitudes of change
Food systems as a whole	Inefficiencies and environmental and health social costs of the global food system $11.9 trillion vs an estimate of the market value of the global food system $10 trillion in 2018: • $1.5 trillion from greenhouse gas emissions • $1.7 trillion from natural capital loss • $2.7 trillion from obesity-related costs • $1.8 trillion from under-nutrition-related costs • $2.1 trillion from pollution, pesticides and antimicrobial resistance • $0.8 trillion from rural welfare losses • $1.3 trillion from food loss and waste and fertilizer leakage (FOLU, 2019)	
Biodiversity loss	• Food production contributes to 60%-70% of total global biodiversity loss (Baltussen et al., 2016, Westhoek et al., 2016). • The loss of wetlands since 1970 has been estimated at about 35% globally (Darrah et al., 2019). • Food systems have created about 24% global forest disturbance (Curtis et al., 2018).	
Depletion of fish stocks	• Commercial fishing is estimated to deplete fish stock by 61% (Westhoek et al., 2016).	
Emissions of greenhouse gases such as carbon dioxide, nitrous oxide and methane	• 13 percent global emissions from agriculture, other than from land use change (Nkonya et al., 2016) and cost USD 0.27 trillions or 49.1 GT CO2 at $ 40/ton (van Nieuwkoop, 2019). • The diet-related social cost of GHG emissions related to current food consumption patterns are estimated to be around USD 1.7 trillion for 2030 for an emissions-stabilization scenario (FAO et al., 2020). • The social cost of carbon is USD 128 per ton CO2 (Baltussen et al., 2016). • Less than one-third of the costs are associated to CO2-eq emissions (Lord, 2020).	• Adoption of organic agriculture, vegan and vegetarian diets to reduce greenhouse gas emissions possibly by 41-74% in 2030 (Marchetti et al., 2020; FAO et al., 2020).
Food loss and waste	• Food waste contributes to about 3–5 % of global warming impacts, more than 20 % of biodiversity pressure, and 30 % of all of the world's agricultural land (Allen & Prosperi, 2016). • Food loss and waste greenhouse gas emissions of meat (poultry, bovine, goat, mutton, and swine) is estimated at 34–38% of all agricultural production-phase greenhouse gas emissions (Porter et al., 2016).	• Environmental and social externalities attributed to the production and purchasing of food that is not consumed (food loss and waste) estimated 1 trillion per year at 2012USD of financial losses and estimated external costs from the lost and wasted food as USD 700 billion for environmental externalities and USD 900 billion (b) for social externalities per year – including USD 394b from GHG emissions, USD 396b from conflict and 333b in lost livelihoods (FAO, 2014).
Food safety (including antimicrobial resistance) and poor food quality	• Economic loss due to insufficient food safety equates to 0.11 (USD trillions)per annum (Jaffee et al., 2019).	

Problem	Estimated costs of current externalities	Estimates of magnitudes of change
Inadequate diets and malnutrition (undernutrition, micronutrient deficiencies and overweight and obesity)	• Globally, diet-related health costs are projected to reach USD 1.3 trillion per year in 2030 (FAO et al., 2020). • More than half (57 percent) of these are direct healthcare costs as they are associated with expenses related to treating the different diet-related diseases (FAO et al., 2020). • In the UK, every £1 spent on food products generates 50 pence in externalities on healthcare systems alone (and £1 in total external costs) (Sustainable Food Trust, 2017). • Current food consumption patterns, health costs are projected to reach an average of USD 1.3 trillion in 2030. 43 percent accounts for indirect costs, including losses in labor productivity (11 percent) and informal care (32 percent) (FAO et al., 2020).	• Springman et al. (2016) estimated the economic benefits of improving diets to be 1–31 trillion US dollars, which is equivalent to 0.4–13% of global GDP in 2050. • Adoption of global dietary guidelines (HGD) would result in 5.1 million avoided deaths per year [95% confidence interval (CI), 4.8–5.5 million] and 79 million years of life saved (CI, 75–83 million) (Springman et al., 2016). • Transitioning towards more plant-based diets that are in line with standard dietary guidelines could reduce global mortality by 6–10% and food-related greenhouse gas emissions by 29–70% compared with a reference scenario in 2050 (Springman et al., 2016). • Using the cost-of-illness approach, we estimate that the health-related cost savings of moving to the diets based on dietary guidelines (HGD) from that assumed in the REF scenario will be 735 billion US dollars per year ($735 billion·y−1) in 2050 with values in the range [based on uncertainties in the cost transfer method (Methods)] $482–987 billion·y−1 (Fig. 2). (Springman et al., 2016). • About two-thirds of the savings (64–66% across the non-reference scenarios) were due to reductions in direct health care-related costs, one-third (31–33%) to less need for unpaid informal care (although this figure is an underestimate because we were unable to obtain estimates of the indirect costs of diabetes), and a small fraction (3–4%) to reduced productivity from lost labor time (Springman et al., 2016). • Transformation to healthy diets by 2050 will require substantial dietary shifts, including a greater than 50% reduction in global consumption of unhealthy foods, such as red meat and sugar, and a greater than 100% increase in consumption of healthy foods, such as nuts, fruits, vegetables, and legumes. However, the changes needed differ significantly by region (Willett et al., 2019). • If any of four alternative diet patterns (FLX, PSC, VEG, VGN resented in the FOA et al., 2020 SOFI report) are adopted, diet-related health costs decrease by USD 1.2–1.3 trillion (95% of the diet-related health expenditure) by 2030 (FAO et al., 2020). • Adoption of any of the four alternative healthy diet patterns set out n FAO et al., 2020) that include sustainability considerations could potentially contribute to significant reductions of the social costs of GHG emissions, ranging from USD 0.7 to USD 1.3 trillion across the four diets (41–74 percent) in 2030 (FAO et al., 2020).
Land degradation	• Food systems contribute to 33% of degraded soils (Westhoek et al., 2016). • Cropland soils have lost 20-60% of their organic carbon content due to land degradation; land degradation affects 1.3 to 3.2 billion people living in poverty in developing countries (Dalin & Outhwaite, 2019). • The annual total natural capital cost of livestock systems in terms of resource use and pollutant emissions is as follows: beef production is USD 1.5 trillion, dairy milk production USD 0.5 trillion and poultry meat production is USD 0.26 trillion (Baltussen et al., 2016).	

Problem	Estimated costs of current externalities	Estimates of magnitudes of change
Land use change	• Land use and land use change, including peatland degradation and deforestation lead to greenhouse gas emissions of 8-10% (FAO et al., 2020). • Average Ecosystem Service Value lost per hectare converted to beef production estimated at USD 1,837 per hectare (Baltussen et al., 2016). • Economic loss due to land use and land cover change in terrestrial ecosystems equates to 0.33 annually (Nkonya et al., 2016) and 0.41 percent of 2018 global GDP (van Nieuwkoop, 2019). • 25 percent of land was degraded due to poor management practices (Nkonya et al., 2016, #) equating to USD0.20 trillions or 0.25 percent of 2018 global GDP (van Nieuwkoop, 2019). • Carbon emissions due to land use changes are estimated to range from US$ 15-24 billion (Baltussen et al., 2016).	
Soil degradation and erosion	• Accelerated soil degradation has reportedly affected as much as 500 million hectares (Mha) in the tropics, and globally 33% of the earth's land surface is affected by some type of soil degradation. • Approximately 33% of soils are moderate to highly degraded due to erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution (Westhoek et al., 2016).	

This Report was prepared by members of the Scientific Group and members of its Research Partners.

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

IN THE AGE OF PANDEMICS, CONNECTING FOOD SYSTEMS AND HEALTH: A GLOBAL ONE HEALTH APPROACH

by Gebbiena M. Bron, J. Joukje Siebenga, Louise O. Fresco

THE CHALLENGES

Local, regional and global food security are affected by the occurrence of epidemics of zoonotic infectious diseases, caused by pathogens that spillover from animals to humans. Currently, this is clearly illustrated by the COVID-19 crisis. Diseases that affect animals and plants also continue to disrupt food security by interrupting the food supply. A One Health approach embraces the notion that the health of animals, people, plants and the environment are inextricably connected. Conversely, climate change, urbanization and mobility innovations should evaluate the risk for new and (re-)emerging human, animal and plant pathogens.

The COVID-19 pandemic lays bare the complex connections between food systems and health. In addition, the pandemic exposes how human health is affected by socio-economic status and how health af-

ABOUT THE AUTHORS

Gebbiena M. Bron, Post-doctoral researcher at the Department of Quantitative Veterinary Epidemiology, Wageningen University, Netherlands.

J. Joukje Siebenga, Programme Manager, Pandemic Preparedness of the Wageningen University, Netherlands.

Louise O. Fresco, President of the Wageningen University and Research Executive Board.

fects economic and social systems in return. The current pandemic is not the first, nor will it be the last. Here, we discuss the link between global food security and healthy people, animals, plants and environment, and how we can better prepare for, and minimize the chance of, future pandemics. We conclude that both public and private parties should strengthen their One Health approach to jointly realize resilient and strong global health and agri-food systems.

Interconnection between ecosystems, human and animal health - zoonotic infectious diseases

COVID-19 is only one example of a zoonosis, a disease caused by the 'successful' transmission, spillover, of a pathogen from animals to humans. SARS-CoV-2 emerged from wildlife. Similarly, ~60% of emerging infectious diseases in humans originated from animals, and ~70% thereof originated from wildlife. Such spillover events most commonly occur where the agri-food system interfaces with natural ecosystems, as this is where humans, domesticated animals and wildlife interact.

Through humanity's long history with animal husbandry and consumption, hygiene practices have evolved, reducing the likelihood of successful spillover events (e.g., food safety, clean water, and elimination of rodents from shelters). However, increasing mobility, population densities and urbanization, as well as the growing length and scale of the global food supply chains, and pressure on natural ecosystems by changing land use have created new challenges and put the need for adaptation of current surveillance and intervention strategies in sharper focus.

Poor human health facilitates infectious disease spread

Sub-optimal human health adds to the favorable conditions for pathogen transmission. Poor nutritional status and the impaired general health of individuals and populations, for example due to the absence of nutritious foods and access to (affordable) health care, increase susceptibility to infectious diseases. Many of the common non-infectious diseases, including obesity, diabetes, cancer and cardio-vascular diseases, impair the body's immune response. These chronic conditions lower barriers to successful pathogen spillover from animals to humans, and subsequent pathogen transmission between people. Similar to other infectious diseases, COVID-19 disproportionately affects those with poor nutritional status and underlying health issues.

IMPACT OF ZOONOTIC INFECTIOUS DISEASES ON FOOD SECURITY

Direct impacts

Large disease outbreaks disrupt the workforce and supply chain. Both the disease and the measures implemented to combat the COVID-19 pandemic have disabled part of the workforce. Such disruptions in the workforce affect the food supply and in many cases workers' income or the economic viability of businesses in the food system. In addition, restrictions on travel limit the movement of workers, disrupting harvest and processing operations. Similarly, trade restrictions limit the movement of goods, affecting supply and demand.

Indirect impacts

Cascading effects of the pandemic increase price volatility, disrupt food security and the livelihoods of those dependent on the food supply chain. Similar to past influenza outbreaks, for example, COVID-19 has changed consumption patterns. Combined with travel and trade restrictions, this has resulted in, among other things, uncertainties in the food supply chain, that have led to volatility in producer and consumer prices. These disrupted markets most severely affect vulnerable populations, e.g., low-income families, leaving them unable to acquire nutritious food or small farm operations. Furthermore, the COVID-19 pandemic is estimated to have put about a third of the jobs in the food value chain at risk (451 million jobs out of ~1.3 billion), disrupting the livelihoods of ~1 billion people.

SARS-CoV-2 and other infectious pathogens in the food chain

Zoonotic and other infectious pathogens can be transmitted via many different routes, including water and food products. The main transmission route of SARS-CoV-2 is the respiratory route, but anecdotal evidence is available for the detection of SARS-CoV-2 genetic material in frozen products (e.g., ice cream). At present, in February 2021, the movement of SARS-CoV-2 through the cold chain is still considered as a possible route of introduction of the pathogen to the urbanized center of Wuhan, China, from where it spread across the world.

The presence of pathogens in food systems may trigger interventions to stop pathogen spread. Although we focus on zoonotic pathogens here, animal and plant diseases and pests should be kept in mind. Similar to zoonotic pathogens, the range and outbreak frequencies of these disruptors of the food supply chain and health are expected to change due to the effects of climate change. Interventions to mitigate zoonotic and notifiable animal and plant pathogens, including transport bans, destruction of crops, and culling, directly impact the food chain and the business and livelihoods of those relying on it.

Adapting the agri-food system to limit pathogen risk

Reducing the likelihood of spillover and onwards transmission risk of pathogens can be achieved through i) reducing the need for natural habitat disruption, ii) smart management of both sides of the interface between natural ecosystems and the agri-food system, and vigilance at the human-animal interface within the agri-food system, and iii) improving overall human, animal and environmental health.

Reducing habitat disruption through sustainable intensification of land use

Sustainable intensification of land use could aid in limiting contact between humans and livestock with natural ecosystems and wildlife. To continue to meet the growing demand for food, further acreage expansion by conversion of natural habitats to agricultural lands is expected in several regions of the world. The pressure on natural ecosystems, caused by the expanding agri-food system, tends to negatively affect the biodiversity, resilience and health of wildlife, and increases the frequency of human, domestic animal and wildlife contact. These factors all contribute to increasing the chance of spillover occurring, hence prompting the argument to reduce natural habitat disruption, and utilize sustainable intensification practices instead to meet the growing food demand.

Smart management and vigilance at the interfaces by surveillance and readiness to intervene

Risk assessments should inform surveillance and readiness strategies to optimize pathogen detection and intervention. Over the past decades we have created an increasingly connected and ready network for pathogens to spread, with the agri-food system being an integral part of this conduit for the onwards spread of pathogens. Here, the domains of food security, safety and health clearly overlap: from hunting practices to livestock farming, from butchering practices at home to slaughterhouses, from trade of live animals on markets and unsafe food preparation practices to contaminated food products in supermarkets, and the length and scale of parts of the global food system.

Detection efforts aimed at preventing pathogen spillover and spread throughout these highly connected networks can be optimized by mapping and assessing the risk, specifically at the human and domestic animal-wildlife interface and in the transport (cold) chain. Targeted sampling and surveillance throughout the system complemented by appropriate hygiene and biosecurity measures form the first steps to preventing shocks to the food system and health.

Optimized surveillance at the human-domestic animal-wildlife interfaces may enable the early detection of (re)emerging pathogens and unexplained disease symptoms (e.g., undiagnosed pneumonia in the case of SARS-CoV-2). This early detection provides the opportunity for early interventions, and re-design of the system. Importantly, clear communication with producers and the public about biosecurity measures, and a rapid and strong unified response are needed to prevent and control potential outbreaks.

Improving overall human, animal and environmental health - A Global One Health approach

Through active engagement with learning and recovery steps following the current pandemic crisis, governments, the private sector and society as a whole have the opportunity to improve and work towards more resilient markets, and create systems to reduce strain on our environment and keep vulnerable populations sheltered from shocks, instead of amplifying their vulnerability (as is happening in COVID-19).

Food security is essential to reducing malnutrition, and it results in improved human health and wellbeing, as well as a human population that is less susceptible to pathogens (e.g., reducing undernutrition, obesity, and resulting diseases). Governmental actions can lead the way to provide food security by ensuring the functioning of the food supply chain and food systems (e.g., minimizing disruption in trade of goods, providing employment services to migrant workers), and communicating clearly to avoid mass panic and disproportional consumer behavior during disease outbreaks. The private sector can weigh their impact on health, considering that their supply chain may be disrupting natural habitats, and that unknown pathogens may emerge at their farms, be transported in their cold chains, or disproportionately affect their staff. These actions, serving the global and national good, should be governed through global institutions to ensure governance of the food system and health for all.

The interconnectedness of environmental, human and animal health can be leveraged in food systems to find unconventional opportunities to improve health. Further research and an improved understanding of the role of the food system in the context of Global One Health may provide additional entry points via the food system for sustainable, culturally acceptable and economically feasible interventions.

TOWARDS FOOD SYSTEM RESILIENCE

Resilient systems allowing for rapid recovery are needed to minimize direct and indirect health effects of shocks to the food system. Shocks, small and large, will continue to disrupt the food system, although efforts to prevent and minimize shocks (as described above for zoonotic infectious diseases) may reduce the frequency and severity of such shocks.

Managing the interdependencies between health and the food system to improve health for all presents many challenges, including a change in mindset. Nevertheless, the dots between the food system and environmental, animal, plant and human health are becoming more connected in global, regional and national initiatives; for example, the materiality matrix in corporate sustainability reports, wherein stakeholder interests and a company's social, economic, and environmental impact are weighted. Moreover, the European Commission is moving towards a code of conduct for participants in the food supply chain, which could be considered at a global level. Most recently, in September 2020, a One Health High-Level Expert Council by UN Environment, FAO, OIE and WHO was created to address risks at the human-animal-environment interface. When consumers, producers and governments combine their efforts and take a Global One Health approach to re-design the agri-food system, significant steps can be made towards food system resilience and better health.

REFERENCES

1. Bakalis, S., Valdramidis, V. P., Argyropoulos, D., Ahrne, L., Chen, J., Cullen, P. J., Cummins, E., Datta, A. K., Emmanouilidis, C., Foster, T., Fryer, P. J., Gouseti, O., Hospido, A., Knoerzer, K., LeBail, A., Marangoni, A. G., Rao, P., Schlüter, O. K., Taoukis, P., Xanthakis, E., Van Impe, J. F. M. 2020. Perspectives from CO+RE: How COVID-19 changed our food systems and food security paradigms. Current Research in Food Science, 3, 166–172. https://doi.org/10.1016/j.crfs.2020.05.003
2. Egger, D., Miguel, E., Warren, S. S., Shenoy, A., Collins, E., Karlan, D., Parkerson, D., Mobarak, A. M., Fink, G., Udry, C., Walker, M., Haushofer, J., Larreboure, M., Athey, S., Lopez-Pena, P., Benhachmi, S., Humphreys, M., Lowe, L., Meriggi, N. F., Wabwire, A., Davis, C.A., Pape, U.J., Graff, T., Voors, M., Nekesa, C., Vernot, C. 2021. Falling living standards during the COVID-19 crisis: Quantitative evidence from nine developing countries. Science Advances, 7(6), eabe0997. https://doi.org/10.1126/sciadv.abe0997
3. FAO and CELAC. 2020. Food security under the COVID-19 pandemic. Rome. https://doi.org/10.4060/ca8873en
4. FAO, IFAD, UNICEF, WFP and WHO. 2020. The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome
5. PAHO. Food security in a pandemic. Retrieved January 28, 2021, from https://www.paho.org/disasters/index.php?option=com_docman&view=download&category_slug=tools&alias=533-pandinflu-leadershipduring-tool-7&Itemid=1179&lang=en
6. Plowright, R. K., Parrish, C. R., McCallum, H., Hudson, P. J., Ko, A. I., Graham, A. L., & Lloyd-Smith, J. O. 2017. Pathways to zoonotic spillover. Nature Reviews Microbiology, 15(8), 502–510. https://doi.org/10.1038/nrmicro.2017.45
7. Swinnen, J., & McDermott, J. 2020. COVID-19 and global food security. International Food Policy Research Institute. https://doi.org/10.2499/p15738coll2.133762
8. Wageningen University & Research. 2020. The effects of COVID-19 on food systems: Rapid assessments. https://www.wur.nl/en/Research-Results/Research-Institutes/centre-for-development-innovation/Our-Value-Propositions/Guiding-Sector-Transformation/The-effects-of-COVID-19-on-food-systems-rapid-assessments.htm
9. Zurayk, R. 2020. Pandemic and Food Security. Journal of Agriculture, Food Systems, and Community Development, 9(3), 17–21. https://doi.org/10.5304/jafscd.2020.093.014

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
Swiss national FAO Committee CNS-FAO

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
June 2021

PATHWAYS TO ADVANCE AGROECOLOGY FOR A SUCCESSFUL TRANSFORMATION TO SUSTAINABLE FOOD SYSTEMS

by Urs Niggli, Martijn Sonnevelt, Susanne Kummer

ABSTRACT

Agroecology is a powerful strategy that reduces the trade-offs between productivity and sustainability. It promotes the diversity of crops and livestock, fields, farms and landscapes, which together are key to improving the sustainability of food and farming systems in terms of long-term productivity, food actors' empowerment and inclusion and environmental health. Agroecology is a bundle of measures taken by farmers that, individually or combined, mobilize biodiversity and ecosystem services for productivity. Ideally, it leads to economically and ecologically resilient production systems that are high-yielding. It is not necessarily a predefined farming system and the shift from simplified by industrial standards to agroecological farms is gradual. The transformation and upscaling of agroecological practices requires changes that affect not only the management of farms, or production and consumption patterns at the food system level, but also the institutional framework conditions and the way in which we measure the performance of agricultural and food systems. In our paper, we describe four domains of transformation - knowledge systems, markets, collaborations and policy coherence - each with enabling and constraining factors.

ABOUT THE AUTHORS

Urs Niggli, Agroecology.science, Frick, Switzerland

Martijn Sonnevelt, World Food System Center, ETH Zurich, Switzerland.

Susanne Kummer, Agroecology.science, Frick, Switzerland

1. INTRODUCTION

Transforming agriculture and food systems in line with Sustainable Development Goals (SDGs) is an imperative that can no longer be ignored or deferred (CNS-FAO, 2019; Eyhorn et al., 2019). In facing up to this challenge, agroecological approaches stand to play an indispensable role by connecting environmental sustainability and social justice of production and consumption. It combines the global challenge of ending hunger with locally adapted solutions and strengthens participation and the mobilization of local actors and their knowledge (HLPE, 2019). Agroecology optimizes the system approach and integrates scientific progress responsibly. To allow for agroecology to exploit its potential, there is a need for transformation that supports the shift from a capital to a more labor-dominated approach that strengthens the social relations of production and moves farming beyond the logic of scale-enlargement, technology-driven intensification and specialization (Van der Ploeg, 2021).

This paper is based on a well-documented multi-stakeholder process of the Swiss National FAO Committee (CNS-FAO) during several years to provide scientific support to the Swiss government and the public on agroecology (CNS-FAO, 2016; CNS-FAO, 2019; CNS-FAO, 2021). The aim of the paper is to highlight the potentials of agroecology for the strengthened effort of the UNFSS 2021 to achieve the SDGs, and highlight the necessary actions for mainstreaming agroecological management practices.

2. GLOBAL CHALLENGES

We identify three major key challenges of global agriculture and food systems: the first challenge is that much of the world's population remains inadequately nourished, with more than 820 million people suffering from hunger. Many more consume low-quality diets, contributing to a substantial rise in the incidence of diet-related illness and obesity (Willet et al., 2019; IPCC, 2019). A second challenge with global impact is the unsustainable way in which food production and consumption patterns substantially exploit the natural resources of soil, water and air (IPBES, 2019). This has caused an immense biodiversity loss (Leclere et al., 2020; IPBES, 2019). Third, greenhouse gas emissions rise dramatically all around the world, with global agriculture causing 23% of anthropogenic greenhouse gas emissions and therefore contributing substantially to global warming (IPCC, 2019).

Not least due to the current Covid-19 pandemic, the fragility and vulnerability of food systems are clearer than ever. Food insecurity and acute hunger have increased, along with more people living in extreme poverty (HLPE, 2020). Providing food for an estimated 10 billion people in 2050 is challenging. It will take a 56% increase in crop calories compared to the base year 2010 (FAO, 2017), in case other issues such as unsustainable consumption patterns, food loss and waste and the use of food crops for animal feedstuff and biofuels are not addressed. The resulting substantial expansion of agricultural land, amounting to 593 million hectares (crop and grassland), must be contained wherever possible if we are not to release large amounts of CO2 equivalents and put biodiversity reserves at risk. Current agriculture should mitigate 11 gigatons of greenhouse gases to meet the Paris climate target of less than 2 degrees Celsius warming (World Resources Institute, 2018). Future solutions must also take into account that by 2050, it is forecasted that 68% of the world's population will live in cities (United Nations, 2019), increasing the importance of urban food production.

3. NEED FOR TRANSFORMATION

A radical transformation of global food systems that addresses both the way we produce, process, trade and consume food and with the same priority the improvement of livelihoods of farmers, farm workers and their families is necessary and does not tolerate any delay. To provide enough food for the global population, several overriding strategies are being pursued, namely a substantial increase in productivity, a sustainable intensification (Godfray and Garnett, 2012) and an ecological intensification (Tittonell, 2014). Agroecology implements the ecological intensification strategy in agricultural practice.

Agroecology offers a powerful means of accelerating the needed transformations. Agroecology as we understand it, has a common framework grounded in the FAO's ten elements (FAO, 2018b). The ten elements of agroecology are interlinked and interdependent. They encompass ecological characteristics of agroecological systems (diversity, synergies, efficiency, resilience and recycling), social characteristics (co-creation and sharing of knowledge, human and social values, culture and food traditions), and enabling political and economic environments (responsible governance, circular and solidarity economy) (FAO, 2018b). These elements come together in a model that relies centrally on the non-exhaustive and non-destructive use of biodiversity and ecosystem services, with off-farm inputs playing a diminished role in production (CNS-FAO, 2019).

Hundreds of thousands of farmers manage their farms with agroecological practices in one way or another, either to improve their own productivity and livelihoods or gain privileged access to markets with certificates. These practices include regenerative conservation agriculture, organic agriculture, agroforestry, permaculture, agro-silvo-pastoral systems, and sustainable pastoralism in rangelands, among others. An even higher number of farmers adopt only one or more selected techniques of agroecology such as integrated nutrient and pest management, introducing semi-natural habitats on the farm, applying no-till arable cropping, or sustainable river basin and groundwater management. Some farmers use bio-fertilizers and bio-protectants instead of agrochemicals, apply intercropping and cover crops to increase the land equivalent ratio (LER), and involve in precision agriculture and climate-smart agriculture. Nonetheless, fully agroecological farms have remained a niche. The classic role of niches is that of a "protective space" or a shelter where future solutions and novel ideas can be tried out (Smith and Raven, 2012). These novel ideas could change or even replace the current regime (Geels, 2011) or paradigm (Beus and Dunlap, 1991).

Although agroecological practices have been successfully implemented on many farms globally and practices such as resource-conserving agriculture continue to spread to more farms and more hectares (Pretty et al., 2006), they have not become mainstream until now. The most salient obstacles to mainstreaming agroecology include that it is currently unknown to the public; the time lag between implementing agroecological practices and observing positive results; weak knowledge and advisory systems; transaction costs; policy incoherence; crucial deficits of landscape-level coordination, incentive systems in research, and compensation for yield reductions; and the need to strengthen the aspect of sufficiency in a sustainability context (IIED, 2016; CNS-FAO, 2021).

The HLPE report (2019) found that to effectively and sustainably address food and nutrition security, it is not sufficient to focus on technological solutions and innovations or incremental interventions only. Food system transformation requires (i) inclusive and participatory forms of innovation governance; (ii) information and knowledge co-production and sharing among communities and networks; and (iii) responsible innovation that steers innovation towards social issues (HLPE, 2019).

Given its holistic approach, transformation to agroecological practices and systems happens at various scales and dimensions from management decisions on farms to complex and erratic transformations resulting from the sum of decisions of various actors within a wider landscape (Anderson, 2021). Therefore, a multi-level perspective has to be taken to understand enabling and disabling factors and processes relevant for mainstreaming (Geels, 2011). Anderson et al. (2021) introduced the term "domains of transformation" within which they described factors, dynamics, structures and processes that constrain or enable transformation in sustainability transitions.

Agroecological transformation can be understood as having five levels (Gliessman, 2015): at level 1, farming systems become more efficient by reducing the use of fertilizers, pesticides or fuel. Level 2 involves replacing agrochemical inputs with more natural ones such as bio-fertilizers and bio-protectants. The way we understand agroecology, it also includes technologies that are safe for the environment and human health and strengthen the systemic processes. Level 3 is about redesigning farming systems with diversified crop rotations, mixed crops, intercropping, leading to better closed cycles of nutrients and organic material. Successful food system transformation also includes increased farmer-consumer collaborations (level 4), either with short distribution channels or internet-based remote applications, and finally a comprehensive transformation of policies, rules, institutions, markets and culture (level 5). The various stages proceed dynamically and in parallel, so that when framework conditions are conducive, a variety of production systems coexist and rural regions continuously change towards a higher degree of sustainability.

In our paper, we address all five levels and propose actions that enable transformation and remove lock-ins. There is no contradiction between mainstreaming agroecology and strongly improving sustainability. Therefore, agroecology plays a crucial role for achieving the SDGs and works remarkably well in theory and practice (COAG, 2018; HLPE, 2019).

4. IMPACT OF AN AGROECOLOGICAL TRANSFORMATION

Agroecology has the potential to contribute to economic growth and decent work (Van der Ploeg et al., 2019), particularly for the rural poor. It contributes to local economic and resource circulation, considerably increases and stabilizes yields of subsistence farmers (Pretty et al., 2006), and reduces costs and external dependencies. Strategies such as diversification, external input reduction and alternative marketing channels have, in some cases, shown to improve farmers' income by 30% (FAO, 2018a). For example, integrated pest management can generate remarkable improvements: in a study in low-income countries, pesticide use declined by 71% and yields grew by 42% (Pretty et al., 2006). A study on 946 farms in France concluded that total pesticide use could be reduced by 42% without negative effects on both productivity and profitability in 59% of the investigated farms (Lechenet et al., 2017). Conservation tillage can improve soil carbon while raising yields, and integrated plant nutrient systems can achieve the same benefits with reduced fertilizer application (Bruinsma, 2003; Pretty et al., 2003; Pretty et al., 2006; Uphoff, 2007).

Furthermore, there are indications that the economic performance of alternative and agroecological farming systems can be comparable to, and is sometimes better than, conventional farming systems (d'Annolfo et al., 2017), and provide greater predictability for farmers (Chappell & LaValle, 2011). With a smaller farm size organic farms can achieve the same profitability as larger conventional farms (Smolik et al., 1995; Rosset, 1999) and that compared to monocultures, agroforestry systems can have a higher return on labor (Armengot et al., 2016). Extensive evidence indicates that agroecology can, on a global scale, provide a level of food security comparable to that of conventional agriculture (Chappell & LaValle, 2011). Under conditions of subsistence agriculture in Sub-Saharan Africa, agroecological methods significantly improved food security and nutritional diversity (Bezner Kerr et al, 2019). Organic agriculture increases the access to food by increasing the quantity of foods produced per household and producing food surpluses that can be sold at local markets, for instance (UNCTAD/UNEP 2011). The yields of organic agriculture outperform traditional subsistence systems. In their study, Pretty et al. (2006) analyzed the impacts of 286 resource-conserving practices in 57 low-income countries and found that these projects led to an average yield increase of 79%. Differences in terms of yield productivity are highly site-specific, as Tittonell (2013) showed for organic agriculture: on marginal sites, organic farming gives equal or slightly higher yields than conventional farming. However, on high-yield sites, organic farming is significantly lower yielding.

Furthermore, agro-biodiversity (a key element of agroecology) is an important driver for making a diverse range of food products available. Although the pathway is complex and not always positively correlated, agricultural diversity plays an important role in improving dietary diversity, which has a strong association with improved nutrition status, particularly micronutrient density of the diets (Fanzo et al. 2013). A recent publication by Bezner Kerr et al. (2021) found evidence for positive outcomes linked to the use of agroecological practices on food security and nutrition (FSN) in households in low- and middle-income countries. While 78% of the studies reported positive outcomes, some studies found mixed outcomes and a few studies reported negative impact on FSN using indicators such as dietary diversity. The most common agroecological practices included crop diversification, agroforestry, mixed crop and livestock systems, and practices improving soil quality, with positive outcomes on FSN indicators such as dietary diversity and household food security.

Yield increases alone will not address our concomitant challenges of hunger, micronutrient deficiencies and obesity. This requires broad ranging system changes that tackle poverty, inequality and barriers to access. The systemic approach based on ethical values, often considered a part of agroecological methods, offers an opportunity to address these issues in an integrated manner. For example, in Madhya Pradesh, India, a development institute provided integrated training in agroecological techniques, health and nutrition to more than 8,500 women from 850 villages over 30 years. This improved livelihoods for the majority of the women and broke the cycle of poverty (FAO, 2018a).

Agroecological systems use natural resources more sustainably and efficiently, and reduce the release of agrochemicals to air, water and soil (Pretty et al., 2017; Lechenet et al., 2017)). Through the enhanced proximity between producers and consumers, agroecology helps raise awareness and reduce food waste, e.g. by redistribution to food bank charities or by repurposing urban organic waste as animal feed or fertilizer (Beausang et al., 2017). Agroecology puts an emphasis on maintaining soil fertility and ecosystem services, which can improve the long-term productivity of the land. As species richness is on average 34% higher in organic farming (Tuck et al., 2014), and organic farming systems have higher floral and faunal diversity than conventional farming systems (Mäder et al., 2002), biodiversity can be conserved and potentially restored within agroecosystems. As organic farming is one of the best-documented agroecological farming systems in scientific terms, these results are fundamentally important for a better understanding of all agroecological practices. Studies have shown that through diverse and heterogeneous agroecological approaches it is possible to preserve and increase wild and domesticated biodiversity by up to 30% (FAO 2018a). The connection between climate action and agroecology is two-way – agroecological systems have the potential to contribute to reducing greenhouse gas emissions and offer management practices to adapt to climate change (FAO, 2018a). Agroecological farming may lead to reduced greenhouse gas emissions by reducing emissions from the production of synthetic fertilizer and carbon capture in the soil (Müller et al., 2017; Smith et al., 2008; Wood and Cowie, 2004). However, these benefits have to be weighed against the lower land use efficiency or the increased requirements on labor of agroecological - especially of organic - systems (Meemken and Qaim, 2018; Clark und Tillmann, 2017). Regarding climate change adaptation, agroecology may improve the resilience of smallholders through the diversification of production and increasing resource use efficiency by integrating social aspects (Altieri et al., 2015; Liebman and Schulte-Moore, 2015). Furthermore, soil fertility, which is higher in agroecological systems, is a key prerequisite for protection against erosion and flood (Seufert and Ramankutty, 2017).

5. THE ROLE OF DIVERSITY FOR FOOD PRODUCTIVITY

One central characteristic of agroecology is diversity (FAO, 2018b). In contrast, most public policies and incentives designed to increase agricultural production carry the risk of reducing the diversity of diets, food systems and landscape. A defining feature of the agroecological approach is diversity of landscape and habitats, of farm activities, of crops grown, of livestock kept and of above and below ground flora and fauna. Agrobiodiversity represents the creativity of life; its irreversible erosion means less capacity to innovate and adapt in the future, especially to climate change (Dury et al., 2019). Substantial improvements in the environmental sustainability of agriculture are achievable now, without sacrificing food production or farmer livelihoods (Davis et al., 2012). While short-term productivity is increasing, there is a clear loss of diversity when traditional varieties or races are replaced by improved varieties (Khoury et al., 2014). This homogenization and high dependency on a few crops at global scale increases the vulnerability to pests, as historically illustrated by many examples in maize, banana and wheat (Dury et al., 2019). Additionally, risks of resistance increase through the wide use of pesticides and antibiotics (Dury et al., 2019). The development of ecosystem services over time in more diverse cropping systems and rotations increasingly displaces the need for external synthetic inputs while still maintaining crop productivity or even increasing yields (Ferrero et al., 2017; Davis et al. 2012).

While socioeconomic factors such as farm commercialization, off-farm income, education or seasonality significantly affect diets of rural households, the linkages between a household’s own agricultural production and dietary diversity are not always clear (Muthini et al., 2020; Sibathu and Qaim, 2018, Bellon et al., 2016). A positive relation between agricultural diversification and diversified diets is shown in different contexts for both subsistence and income-generating household strategies (Jones, 2017; Muthini et al., 2020; Sibathu and Qaim, 2018). In a comparative analysis including 23 studies, Jones (2017) demonstrated that agricultural biodiversity has a small but clear and consistent association with more diverse household- and individual-level diets. These various relations between diversity and food and nutrition security calls for a production strategy combining local productivity and yield stability to make best use of between- and within-crop diversification to increase long-term food and nutritional security.

Agroecological approaches elevate the role of farmers and other food producers in associated knowledge and value chains. This is especially the case for the knowledge and experience of women, as women play a key role in all stages of food production in almost all regions around the world, encompassing their practical knowledge on biodiversity, including seeds, on food preservation and recipes. Women’s control of farm level decision making is an important determinant in understanding household-level diet diversity, expressed by a positive relation between agricultural biodiversity and household diet diversity for households headed by women (Jones et al., 2014). Agroecology can create better opportunities for women by integrating diverse work tasks and specific forms of knowledge, providing a more significant role for women in the household and farm economy. As agroecology, through low initial investment costs and knowledge-intensive technologies, is better accessible to women, it also fosters their economic opportunities and autonomy. In its political dimension, agroecology seeks to achieve and implement a just system (Seibert et al., 2019).

6. DOMAINS OF TRANSFORMATION WITH ENABLING AND RESTRAINING FACTORS

The domains of transformation that we want to address are i) strengthening knowledge on agroecology, ii) working with markets, iii) enhancing cooperation, and iv) ensuring policy coherence to create a conducive policy context for agroecology. These four domains address both agroecological practices (levels 1,2 and 3 of Gliessman, 2015) and the wider food system changes (levels 4 and 5).

6.1 Strengthening knowledge (research, education and innovation) on agroecology

The knowledge and advisory systems required to support agroecology and build the capacity of actors are insufficient (Wezel et al., 2018). A systems-oriented, transdisciplinary, and long-term field research approach is lacking. Instead, current global knowledge and research systems promote fragmented short-term output (Aboukhalil, 2014; Edwards & Roy, 2017).

In 2011, total global public and private investment in AgR4D exceeded 70 billion US dollars (in purchasing power parity dollars) (Pardey et al., 2016). Current global R&D investments focus mainly on major staple crops. More nutrient-dense crops such as pulses, fruits and vegetables, as well as orphan crops, are often neglected (GloPan, 2016; HLPE, 2019). The Consortium of International Agricultural Research Centres (CGIAR) Research Programs still focus largely on breeding and efficiency in production systems, rather than expanding its scope to a food system perspective (Biovision & IPES-Food, 2020). A study analyzing 728 AgR4D projects with a total budget of 2.56 billion US dollars showed that local and regional value chains, traditional knowledge and cultural aspects of food systems are underrepresented in research programs, while only a handful of projects take a participatory approach to research (Biovision & IPES-Food, 2020). The public investment in agroecological approaches is estimated to range between 1 and 1.5 % of total agricultural and aid budgets (HLPE, 2019). In order to transform the current food system, it is crucial for research projects to address and include key aspects of socioeconomic and political change, such as decent working conditions, gender equality (Biovision & IPES-Food, 2020) and the important role of young and highly qualified people.

To tackle these challenges, the research focus should be shifted to agroecological principles, research activities should be better contextualized and funding mechanisms should be adequately altered, providing more funding for systemic, interdisciplinary and transdisciplinary research. This also usually requires longer funding periods.

Besides providing adequate funding for agroecological research, it is also crucial to break down institutional silos and enhance systems thinking in research and training. Interdisciplinary courses at the graduate and undergraduate level should include non-academic actors. Educational structures and programs are already showing signs of evolving towards systems analysis with several universities recently opening food system centers or units that break down the traditional structures of research. Knowledge for agroecological innovations requires front-end research, but needs also to be combined with "know-how" and "do-how" (Saliou et al., 2019). Therefore, tools and platforms allowing for the transdisciplinary exchange and development of knowledge are key, particularly with young people and women.

It is hence key to provide training that includes practitioner-led learning and building a culture of accountability where research is undertaken with and for farmers as the ultimate beneficiaries. Currently, these agents of change for agroecology are rarely among the recipients of research funding. Farmers' intuition and tacit knowledge, practical know-how and scientific R&D can be harnessed together to yield solutions that are better suited to their particular context and are more quickly implemented.

Public support should be provided to further develop agroecological curricula at colleges and universities and facilitate exchange between experienced and interested stakeholders (from research, civil society, donor organizations and private sector). Establishing a network of decentralized centers of excellence in agroecology would further reinforce system thinking and enhance exchanges between different knowledge holders (Biovision & IPES-Food, 2020; HLPE, 2019). New methodologies developed at universities and research centers such as co-creation of knowledge and citizen science using digital tools enhance participation and transdisciplinarity.

Implementing agroecological practices successfully is knowledge-intensive and requires more experimentation and site-specific adaptation than standardized, industrial farming practices (HLPE, 2019). This potentially makes agroecological practices attractive to young people, and requires the skills and expertise of a diversity of practitioners and specialists, including farmers, researchers and extensionists. In many parts of the world, private extension services financed by the sales of goods and services are predominant. When it comes to developing extension systems that align with agroecological approaches, publicly funded extension services are crucial. Tackling them requires re-configuring knowledge and extension systems in ways that place a much greater emphasis on participation and social learning, e.g. farmer-to-farmer learning and on-farm demonstrations. Expanding the use of low-cost information and communication technology (ICT) such as interactive radio, use of apps, videos, and social media is an effective means to reach large numbers of people, including youth. ICT has the added advantage of being highly customizable to suit specific contexts, while digital tools are also highly versatile. Widening access will also require innovative approaches in the delivery of information, so that the private sector, farmer groups, volunteers, social workers and youth entrepreneurs can become partners in extension and advisory systems (Fabregas, Kremer & Schilbach, 2019).

6.2 WORKING WITH MARKETS

Agroecological systems are more diversified in terms of farm activities and tend to yield a greater number of crop or livestock products, but with a smaller volume of each product. This can limit market and processing opportunities and requires higher levels of knowledge and risk-taking. Furthermore, local marketing structures have in many regions been replaced by food retail chains, with food producers finding themselves in the weakest position along the value chain.

Only 10-12% of all agricultural products are traded on international markets, and most food in the world is produced, processed, distributed and consumed within local, national and/or regional food systems (CSM, 2016). The Covid-19 pandemic has shown that sustainable local food systems are crucial for maintaining stable access to food when the global system fails. Supporting short supply chains and alternative retail infrastructures with stronger participation and control of more and various food system actors such as farmers' markets, fairs, food policy councils, and local exchange and trading systems, may enhance farmers' livelihoods and increase access to local, sustainably-produced and diverse food (Hebinck et al., 2015). More support should be given to develop local and regional markets, processing hubs and transportation infrastructures that provide greater processing and handling capacities for fresh products from small and medium-sized farmers who adopt agroecological and other innovative approaches, and to improve their access to local food markets (Wezel in Herren et al., 2020). Strengthening local food systems depends on enhancing local authorities' (e.g. municipalities) capacity to design favorable local policies. These in turn could work to enhance direct connection between producers and consumers, provide public facilities, support farmers´ associations in building strong local marketing networks, and entrench participatory guarantee systems (PGS) to certify organic and agroecological producers (HLPE, 2019).

Farmers (particularly smallholders, women and young people), producer organizations, input providers and businesses transforming their operations based on agroecological principles need access to credit and alternative investment platforms with low capital costs. Not only farmers but food systems actors in general require access to secure and low-cost capital to absorb risks (e.g. momentary lower profitability) in the course of converting towards more sustainable business models. Investments into FinTech research which accelerate and facilitate the access to transformational capital (e.g. mobile microfinance, peer-to-peer lending platform and crowdfunding) must be given due priority.

Food prices and the price for food waste should be "right", internalizing external costs and enhancing positive externalities. This means that both the nutritional value of a food item as well as its production- and consumption-associated costs along the entire food value chain should be taken into account (FAO, 2018c). However, an increase in food prices has a negative impact on the ability of those on low incomes to buy food of appropriate quality. Similarly, the Eat-Lancet Commission states that "food prices should fully reflect the true costs of food". However, options that support vulnerable population groups and protect them from the negative consequences of the potential increase of food prices need to be considered (Willett et al., 2019). Besides food prices, financial and fiscal incentives of unsustainable production systems also have a significant influence on current food systems. To allow for food system transformation, the creation of a shared understanding of all of the positive and negative externalities of the food system, as well as of the best approaches to defining reduction targets is crucial (Perotti, 2020).

6.3 ENHANCING COLLABORATION

Agroecological practices often depend on collective action across a landscape scale, involving multiple farms and a range of actors. Furthermore, agricultural innovations respond better to local challenges when they are co-created through participatory processes and endorsed by local-specific knowledge. Collaboration and coordination across local, regional and national levels is key to support the active involvement and self-organization of food system actors such as producers, private sector investors, academia, civil society and governments. There is growing evidence from literature highlighting the need for collective action and coordination at the local level to create favorable sociotechnical conditions for agroecological transition (Lucas et al., 2019). Agroecological innovations to be successful and implemented at larger scale, require mobilizing a growing range of stakeholders with multiple perspectives (Triboulet et al., 2019). However, agroecological farmers often value community cooperation higher and as more important compared to colleagues working in non-agroecological farming systems. This is in line with agroecology principles in which the links to members of the community for knowledge sharing and problem-solving are key to strengthen sustainability and resilience (Leippert et al., 2020). Through interactions with other stakeholders and networks, farmers and other agents of change are supported to strengthen existing initiatives and further develop collective awareness, identity, and agency around agroecological management issues (Chable et al., 2020). This requires higher levels of coordination and increases transaction costs.

Multi-stakeholder dialogues built on evidence-based arguments can help to bring together different perspectives, as long as they are developed in an inclusive manner (HLPE, 2019). Agricultural research projects and partnerships too often remain focused on one-way knowledge transfer via institutes based in the Global North. It is therefore crucial not only to promote a shift towards agroecological research but also to rebalance North-South power relations through equal research partnerships and direct access to research funding. Additionally, increased funding to build lasting bridges for South-South collaboration is needed. Supporting the emergence of long-term partnerships and coalitions with a focus on agroecology, local ownership, and the meaningful involvement of social movements and farmers' organizations is equally important. In parallel, the Public-Private Partnership model that is so central to current AgR4D needs to be continually scrutinized with regard to the delivery of benefits vis-à-vis the SDGs (Biovision & IPES-Food, 2020).

Social movements associated with agroecology have often arisen in response to agrarian crises and have joined forces to initiate transformation of agriculture and food systems. Agroecology has become the overarching political framework under which many social movements and peasant organizations around the world assert their collective rights and advocate for a diversity of locally adapted agriculture and food systems mainly practiced by small-scale food producers. These social movements highlight the need for a strong connection between agroecology, the right to food and food sovereignty. They position agroecology as a political struggle, requiring people to challenge and transform existing power structures (HLPE, 2019).

6.4 Ensuring policy coherence to create a conducive policy context for agroecology

To take agroecology to the next level, a solid governance structure combined with a set of coherent policy measures are essential (Eyhorn et al., 2019). Laws, regulations, publicity awareness campaigns and fiscal incentives are all part of a framework that should serve society. Many policy measures have negative impacts on the goals of different national strategies and policy objectives such as climate, biodiversity, soil protection, animal welfare, environmental protection, nutrition and health. Current agricultural and trade policies, including subsidy schemes, still favor intensive, export-oriented production of a few crops as well as the intensive use of fossil fuel and agrochemical inputs and must be revised to address multi-functionality of agriculture (Eyhorn et al., 2019; HLPE, 2019). The holistic nature of agroecology requires a well-coordinated coherent policy framework and a shift from a production focused perspective to one including new indicators covering nutritional aspects, environmental impact and long-term stability of the system. Such a holistic accounting of the performance of food production would allow for an evaluation of all of the positive and negative externalities (Perotti, 2020).

International trade relations should include or allow for specific tools or mechanisms to foster the marketing of products derived from agroecological systems. Bi- and multilateral trade agreements should not include policies or ask for laws that might hinder agroecological production and even put its central elements as defined by FAO at risk.

Agriculture benefits - at varying degrees - from government support measures all over the world. In Europe, these are mainly direct payments, which are paid out to farms to support their income. "Public money for public goods" is a claim that environmental politicians and NGOs have been making for 30 years. Fortunately, there is a growing consensus that this would be an effective greening strategy and would bring major benefits to agroecology. Piñeiro et al. (2020) investigated which measures were most effective in promoting sustainability in agriculture. By far the most effective measures are government-supported eco-schemes in all political, economic and social contexts, worldwide. Education, extension or market incentives (demand) come second. This relates to the fact that the market only settles private goods and services, but not public goods. The important function of state intervention (direct payments, investment subsidies, contributions to research, education and advisory services) is therefore to minimize the conflict of goals between private and public goods and functions. If the funds available for the various policy areas were channeled into agroecology, a huge transformative force would develop very quickly.

One major challenge is that on average, conversion to agroecological systems typically results in a short-term reduction of yields (Tittonell, 2014) that needs to be compensated by cost savings, higher product prices or policy support measures to ensure the economic viability of the farms. Additionally, the definition of sustainability in agriculture and food systems must be broadened beyond the efficiency narrative. Sufficiency means reducing resource consumption by adopting sustainable diets, reducing the demand for certain goods (e.g. feedstuff and biofuels produced on arable land), or increasing the demand of goods with relative advantages that cause less emissions and resource depletion under certain situations and in certain locations, and by reducing food waste. Although the efficient use of natural and human-made resources remains important, efficiency alone is often offset by rebound effects (Polimeni et al. 2008) such as a higher consumption or wastage. Global mass-flow models show that narratives based on sufficiency can successfully reduce the trade-offs between productivity and eco-stability (Schader et al., 2015; Müller et al., 2017).

Making use of existing public purchasing obligations can provide economic and political opportunities to implement policy and build new and innovative socioeconomic relationships that create sustainable food systems. Public procurement of sustainably-produced food, for example, can support low-income and other groups within schools, hospitals and other public institutions, setting off mutually reinforcing circuits. Interventions that focus on local procurement of sustainably-produced food for school feeding programs, or that target groups vulnerable to food insecurity, to realize food sovereignty at local and state level, can be effective in addressing FSN while supporting sustainable food systems (Barrios et al., 2020). These initiatives can also support safe, decent, meaningful employment for marginalized groups, including young people and low-income workers within the food system.

International guidance to comprehensively measure outcomes of agroecological farming systems are the Tool for Agroecology Performance Evaluation (TAPE), SAFA Guidelines of FAO (2013) or UN System of Environmental Economic Accounting (SEAA). Research projects in general and technology development in particular should be subjected to a holistic, multi-criteria assessment measuring against the elements of agroecology: FAO's TAPE (FAO, 2019), the Agroecology Criteria Tool (ACT), the growing body of work on 'true cost accounting' and specific metrics like the LER are at hand (Biovision & IPES-Food, 2020). Multi-criteria sustainability assessment tools for farms and food business are very helpful in assessing complexity and holistic sustainability and can accelerate transformation processes in agriculture and nutrition (Mottet et al., 2020).

7. CONCLUSIONS: CONTRIBUTION OF AGROECOLOGY TO THE SDGS

The SDGs recognize the strong interconnectivity among development goals and stress the need for holistic approaches and profound transformation of human activity across multiple dimensions and at multiple scales (Barrios et al., 2020). Due to the fundamental importance of agriculture, the state of agriculture and food systems directly or indirectly affects all seventeen of these goals. Agroecology provides one tool to help build sustainable food systems and thus contribute to the ambitious targets laid out under the SDGs (Farrelly, 2016). In particular, agroecology can contribute to no poverty (SDG 1), zero hunger (SDG 2), good health and wellbeing (SDG 3), decent work and economic growth (SDG 8), responsible consumption and production (SDG 12), climate action (SDG 13) and life on land (SDG 15).

Agroecological approaches are increasingly called upon to play a greater role in contributing to achieve sustainable global food systems. Numerous promising examples demonstrating the potential of agroecology to stimulate and drive sustainable transition of food systems around the world were presented in a stakeholder paper (CNS-FAO, 2021). If we implement the concept and at the same time apply a coherent policy set, agroecology contributes to sustainable and resilient food production systems that help maintain ecosystems and that progressively improve land and soil quality. It further helps in maintaining the genetic diversity of seeds, cultivated plants and domesticated animals. Through the promotion of reduced, alternative (non-chemical) and safe application of crop protection products, agroecology can reduce risks associated with agrochemical exposure, thus positively influencing the health of rural workers and of consumers.

All of these potential benefits of agroecology mentioned above combined with long-term productivity, social wellbeing and improved agency, reduced food waste and loss and a sufficiency-oriented agricultural production require a rethinking of both the indicators and the way in which we measure performance of agricultural and food systems (Mottet et al, 2020). Additionally, a coherent policy framework is necessary that is able to break policy silos and improve governance structures in many countries to allow for a higher self-control of resource base, reduce the dependency of traditional market mechanisms controlled by capital through the construction of new, nested, markets, a strong backing reliance of high quality of labor, exchange of experiences and the availability of skill-oriented technologies, and a high degree of self-regulation at the territorial level (Van der Ploeg, 2021). All of these elements are strengthening farming as an interesting, fulfilling profession, attractive for young people. To allow agroecology to play a role in food system transformation, different governance levels and different departments, teams and stakeholder groups need to closely work together to define the key performance indicators for sustainable food systems and a policy frame aiming to reduce the amount of trade-offs. Promising examples of agroecological practices have developed and spread globally (CNS-FAO, 2021), and the increasing awareness of society for the urgency of food systems transformation increase the pressure on decision-makers to substantially support the development towards sustainable food systems. Strengthening knowledge systems, working with markets, enhancing collaboration between food system actors and creating an enabling policy environment will be crucial for this development.

REFERENCES

1. Aboukhalil, R. (2014): The rising trend in authorship. The Winnower 2:e141832.26907. https://doi.org/10.15200/winn.141832.26907
2. Altieri, M.A., Nicholls, C.I., Henao, A. & Lana, M.A. (2015): Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development 35(3):869-890. https://doi.org/10.1007/s13593-015-0285-2
3. Anderson, C.R., Bruil, J., Chappell, M.J., Kiss, C. & Pimbert, M.P. (2021): Conceptualizing processes of agroecological transformations: from scaling to transition to transformation. In: Agroecology Now!. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-61315-0_3
4. Armengot, L., Barbieri, P., Andres, C., Milz, J. & Schneider, M. (2016): Cacao agroforestry systems have higher return on labor compared to full-sun monocultures. Agronomy for Sustainable Development 36(4):1-10. https://doi.org/10.1007/s13593-016-0406-6
5. Barrios, E., Gemmill-Herren, B., Bicksler, A., Siliprandi, E., Brathwaite, R., Moller S., Batello, C. & Tittonell, P. (2020): The 10 Elements of Agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. Ecosystems and People 16(1): 230-247, https://doi.org/10.1080/26395916.2020.1808705
6. Beausang, C., Hall, C. & Toma, L. (2017): Food waste and losses in primary production: Qualitative insights from horticulture. Resources, Conservation and Recycling 126: 177-185. https://doi.org/10.1016/j.resconrec.2017.07.042
7. Bellon, M. R., Ntandou-Bouzitou, G. D., & Caracciolo, F. (2016): On-farm diversity and market participation are positively associated with dietary diversity of rural mothers in southern Benin, West Africa. PloS one 11(9): e0162535. https://doi.org/10.1371/journal.pone.0162535
8. Beus, C. & Dunlap, R. (1991): Measuring adherence to alternative vs. conventional agricultural paradigm: a proposed scale. Rural Sociology 56(3): 432-460. https://doi.org/10.1111/j.1549-0831.1991.tb00442.x
9. Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., Msachi, R., Odei Boateng, G., Snapp, S., Chitaya, A., Maona, E., Gondwe, T., Nkhonjera, P., & Luginaah, I. (2019): Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. Agriculture, Ecosystems & Environment 279: 109-121, https://doi.org/10.1016/j.agee.2019.04.004.
10. Bezner Kerr, R., Madsen, S., Stüber, M., Liebert, J., Enloe, S., Borghino, N., Parros, P., Munyao Mutyambai, D., Prudhon, M. & Wezel, A. (2021): Can agroecology improve food security and nutrition? A review. Global Food Security 29: 100540. https://doi.org/10.1016/j.gfs.2021.100540.
11. Biovision & IPES-Food (2020): Money Flows: What is holding back investment in agroecological research for Africa? Biovision Foundation for Ecological Development & International Panel of Experts on Sustainable Food Systems. http://www.ipes-food.org/_img/upload/files/Money%20Flows_Full%20report.pdf
12. Bruinsma, J. (ed.) (2003): World agriculture: towards 2015/2030; An FAO perspective. Earthscan Publications Ltd, Taylor & Francis Group. London & New York. http://www.fao.org/3/y4252e/y4252e.pdf
13. Chable, V., Nuijten, E., Costanzo, A., Goldringer, I., Bocci, R., Oehen, B., Rey, F., Fasoula, D., Feher, J., Keskitalo, M. & Koller B. (2020): Embedding Cultivated Diversity in Society for Agro-Ecological Transition. Sustainability 12: 784. https://doi.org/10.3390/su12030784

14. Chappell, M.J. & LaValle, L.A. (2011): Food security and biodiversity: can we have both? An agroecological analysis. Agriculture and Human Values 28: 3-26. https://doi.org/10.1007/s10460-009-9251-4
15. Clark, M. & Tilman, D. (2017): Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters 12:064016. https://doi.org/10.1088/1748-9326/aa6cd5
16. CNS-FAO (2016): Working towards Sustainable Agriculture and Food Systems. A discussion paper. Swiss National FAO Committee (CNS-FAO), September 2016.
17. CNS-FAO (2019): Agroecology as a means to achieve the Sustainable Development Goals. A discussion paper. Swiss National FAO Committee (CNS-FAO), February 2019.
18. CNS-FAO (2021): Pathways to advance agroecology. Overcoming challenges and contributing to sustainable food systems transformation. Swiss National FAO Committee (CNS-FAO), March 2021.
19. COAG (2018): Agroecology: from advocacy to action. Discussion paper for the Twenty-sixth Session of the FAO Committee on agriculture on 1-5 October 2018. Rome.
20. CSM (2016): Connecting Smallholders to markets. An analytical guide. The Civil Society Mechanism (CSM). http://www.fao.org/family-farming/detail/en/c/1104374/
21. D'Annolfo, R., Gemmill-Herren, B., Gräub, B., & Garibaldi, L.A. (2017): A review of social and economic performance of agroecology. International Journal of Agricultural Sustainability 15: 632–644. https://doi.org/10.1080/14735903.2017.1398123
22. Davis, A.S., Hill, J.D., Chase, C.A., Johanns, A.M. & Liebman, M. (2012): Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. PLoS ONE 7: e47149. https://doi.org/10.1371/journal.pone.0047149
23. Dury, S., Bendjebbar, P., Hainzelin, E., Giordano, T. & Bricas, N., (eds) (2019): Food Systems at risk: new trends and challenges. Rome, Montpellier, Brussels, FAO, CIRAD and European Commission. https://doi.org/10.19182/agritrop/00080
24. Edwards, M.A. & Roy, S. (2017): Academic research in the 21st century: maintaining scientific integrity in a climate of perverse incentives and hypercompetition. Environmental Engineering Science 34: 51-61. https://doi.org/10.1089/ees.2016.0223
25. Eyhorn, F., Muller, A., Reganold, J.P., Frison, E., Herren, H.R., Luttikholt, L., Mueller, A., Sanders, J., Scialabba, N.E.H., Seufert, V. & Smith, P. (2019): Sustainability in global agriculture driven by organic farming. Nature Sustainability 2:253-255. https://doi.org/10.1038/s41893-019-0266-6
26. Fabregas, R., Kremer, M. & Schilbach, F. (2019): Realizing the potential of digital development: The case of agricultural advice. Science 336: 6471. https://doi.org/10.1126/science.aay3038
27. Fanzo, J., Hunter, D., Borelli, T., & Mattei, F. (eds) (2013): Diversifying food and diets – using agricultural biodiversity to improve nutrition and health. Taylor & Francis Group. London & New York. https://www.bioversityinternational.org/e-library/publications/detail/diversifying-food-and-diets/.
28. FAO (2017): The future of food and agriculture – Trends and challenges. Rome. http://www.fao.org/3/a-i6583e.pdf
29. FAO (2018a): FAO'S work on agroecology - a pathway to achieving the SDGs. http://www.fao.org/3/i9021en/I9021EN.pdf
30. FAO (2018b): The 10 elements of agroecology: guiding the transition to sustainable food and agricultural systems. Rome. http://www.fao.org/3/i9037en/i9037en.pdf
31. FAO (2018c): The future of food and agriculture: Alternative pathways to 2050. http://www.fao.org/3/CA1553EN/ca1553en.pdf
32. FAO (2019): TAPE Tool for Agroecology Performance Evaluation 2019 – Process of development and guidelines for application. Test version. Rome. http://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1257355/
33. Farrelly, M. (2016): Agroecology contributes to the Sustainable Development Goals. Farming Matters 32: 32-34.
34. Ferrero, R., Lima, M., Davis, A.S. & Gonzalez-Andujar, J.L. (2017): Weed Diversity Affects Soybean and Maize Yield in a Long Term Experiment in Michigan, USA. Frontiers in Plant Science 8:236. https://doi.org/10.3389/fpls.2017.00236
35. Geels, F. W. (2011): The Multi-level Perspective on Sustainability Transitions: Responses to Seven Criticisms. Environmental Innovation and Societal-Transitions, 1: 24–40. https://doi.org/10.1016/j.eist.2011.02.002
36. GloPan (2016): The cost of malnutrition: why policy action is urgent. Technical Brief No. 3. http://www.glopan.org /sites/default/files/pictures/CostOfMalnutrition.pdf
37. Gliessman, S.R. (2015): Agroecology: The Ecology of Sustainable Food Systems. 3rd Edition. Boca Raton, FL, USA, CRC Press, Taylor & Francis Group. ISBN 9781439895610
38. Godfray, Ch. & Garnett, T. (2014): Food security and sustainable intensification. Philosophical transactions of the Royal Society. Series B,

Biological sciences. 369: 20120273. https://doi.org/10.1098/rstb.2012.0273.
39. Hebinck, P., Schneider, S. & Van Der Ploeg, J.D. (eds) (2014): Rural development and the construction of new markets. London: Routledge. ISBN 9780367869298
40. HLPE (2019): Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf
41. HLPE (2020): Issues Paper on the Impact of COVID-19 on Food Security and Nutrition (FSN) by the High-Level Panel of Experts on Food Security and nutrition (HLPE). http://www.fao.org/3/cb1000en/cb1000en.pdf
42. IFPRI (2016): 2016 Global Food Policy Report. International Food Policy Research Institute, Washington DC. http://dx.doi.org/10.2499/9780896295827
43. IIED (2015): Summary report of the high-level workshop on scaling up agroecology to achieve the SDGs. https://infohub.practicalaction.org/bitstream/handle/11283/594772/Agroecology_Workshop.pdf?sequence=1&isAllowed=y
44. IPBES (2019): The Global Assessment Report on Biodiversity and Ecosystems Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). https://ipbes.net/fr/node/35274
45. IPCC (2019): Climate Change and Land. IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/srccl/
46. Jones, A.D., Shrinivas, A. & Bezner-Kerr, R. (2014): Farm production diversity is associated with greater household dietary diversity in Malawi: findings from nationally representative data. Food Policy 46:1–12. https://doi.org/10.1016/j.foodpol.2014.02.001
47. Khourya, C.K., Bjorkmanc, A.D., Dempewolfd, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L.H. & Struik, P.C. (2014): Increasing homogeneity in global food supplies. Proceedings of the National Academy of Sciences, 111: 4001-4006; https://doi.org/10.1073/pnas.1313490111
48. Lechenet, M., Dessaint, F., Py, G., Makowski, D. & Munier-Jolain, N., (2017): Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nature Plants 3: 17008. https://doi.org/10.1038/nplants.2017.8
49. Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H., Chaudhary, A., De Palma, A., DeClerck, F.A., Di Marco, M., Doelman, J.C., Dürauer, M. & Freeman, R. (2020): Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585: 551–556. https://doi.org/10.1038/s41586-020-2705-y
50. Leippert, F., Darmaun, M., Bernoux, M., Mpheshea, M., Müller, A., Geck, M., Herren, M., Irungu, W., Nyasimi, M., Sene, J.M. & Sow, M. (2020): The potential of agroecology to build climate-resilient livelihoods and food systems. Rome. FAO and Biovision. https://doi.org/10.4060/cb0438en
51. Liebman, M.Z. & Schulte-Moore, L.A. (2015): Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. Elementa: Science of the Anthropocene 3:000041. https://doi.org/10.12952/journal.elementa.000041
52. Lucas, V., Gasselin, P. & Van Der Ploeg, J.D., (2019): Local inter-farm cooperation: A hidden potential for the agroecological transition in northern agricultures. Agroecology and Sustainable Food Systems 43: 145-179. https://doi.org/10.1080/21683565.2018.1509168
53. Mäder P., Fliessbach A., Dubois D., Gunst L., Fried P. & Niggli U. (2002): Soil fertility and biodiversity in organic farming. Science 296: 1694-1697. https://doi.org/10.1126/science.1071148
54. Meemken, E.M. & Qaim, M. (2018): Organic agriculture, food security, and the environment. Annual Review of Resource Economics 2018 10: 39-63. https://doi.org/10.1146/annurev-resource-100517-023252
55. Mottet, A., Bicksler, A., Lucantoni, D., De Rosa, F., Scherf, B., Scopel, E., López-Ridaura, S, Gemmil-Herren, B., Bezner Kerr, R., Sourisseau, J.-M., Petersen, P., Chotte, J.-L., Loconto, A. & Tittonell, P. (2020): Assessing Transitions to Sustainable Agricultural and Food Systems: A Tool for Agroecology Performance Evaluation (TAPE). Frontiers in Sustainable Food Systems. 4:579154. https://doi.org/10.3389/fsufs.2020.579154
56. Müller, A., Schader, C., Scialabba, N.E.H., Bruggemann, J., Isensee, A., Erb, K.H., Smith, P., Klocke, P., Leiber, F., Stolze, M. & Niggli, U. (2017): Strategies for feeding the world more sustainably with organic agriculture. Nature Communications 8: 1290. https://doi.org/10.1038/s41467-017-01410-w
57. Muthini, D., Nzuma, J., & Nyikal, R. (2020): Farm production diversity and its association with dietary diversity in Kenya. Food Security 12: 1107–1120. https://doi.org/10.1007/s12571-020-01030-1
58. Pardey, P.G., Chan-Kang, C., Dehrner, S.P., & Beddow, J.M. (2016): Agricultural R&D is on the move. Nature News, 537(7620): 301. https://doi.org/10.1038/537301a

59. Perotti, A. (2020): Moving Towards a Sustainable Swiss Food System: An Estimation of the True Cost of Food in Switzerland and Implications for Stakeholders. Master thesis, ETH Zurich. https://doi.org/10.3929/ethz-b-000473289
60. Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A.M., Kinengyere, A., Morales Opazo, C., Owoo, N., Page, J.R., Prager, S.D. & Torero, M. (2020): A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nature Sustainability 3: 809–820. https://doi.org/10.1038/s41893-020-00617-y
61. Polimeni, J.M., Mayumi, K., Giampietro, M., & Alcott, B. (2008): The Jevons Paradox and the Myth of Resource Efficiency Improvements. Routledge, ISBN 978-1-84407-462-4.
62. Pretty, J., Morison, J.I. & Hine, R.E. (2003): Reducing food poverty by increasing agricultural sustainability in developing countries. Agriculture, Ecosystems & Environment 95:217-234. https://doi.org/10.1016/S0167-8809(02)00087-7
63. Pretty, J.N., Noble, A.D., Bossio, D., Dixon, J., Hine, R.E., Penning de Vries, F.W.T. & Morison, J.I.L. (2006): Resource-conserving agriculture increases yields in developing countries. Environmental Science & Technology, 40: 1114–1119. https://doi.org/10.1021/es051670d
64. Rosset, P.M., Machín, Sosa B., Roque Jaime, A.M. & Ávila Lozano, D.R. (2011): The Campesino-to-Campesino agroecology movement of ANAP in Cuba: social process methodology in the construction of sustainable peasant agriculture and food sovereignty. The Journal of peasant studies 38: 161-191. https://doi.org/10.1080/03066150.2010.538584
65. Salliou, N., Muradian, R. & Barnaud, C. (2019): Governance of Ecosystem Services in Agroecology: When Coordination is Needed but Difficult to Achieve. Sustainability 11:1158. https://doi.org/10.3390/su11041158
66. Schader, C., Müller, A., Scialabba, N.E., Hecht, J., Isensee, A., Erb, K.H., Smith, P., Makkar, H.P.S., Klocke, P., Leiber, F., Schwegler, P., Stolze, M. & Niggli, U. (2015): Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. Journal of the Royal Society Interface 12: 20150891. https://doi.org/10.1098/rsif.2015.0891
67. Seibert, I.G., Sayeed, A.T., Georgieva, Z., and Guerra, A. (2019): Without feminism, there is no agroecology. https://www.righttofoodandnutrition.org/files/rtfn-watch11-2019_eng-42-50.pdf
68. Seufert, V. & Ramankutty, N. (2017): Many shades of gray—The context-dependent performance of organic agriculture. Science Advances 3:e1602638. https://doi.org/10.1126/sciadv.1602638
69. Sibhatu, K.T. & Qaim, M. (2018): Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. Food Policy 77: 1-18. https://doi.org/10.1016/j.foodpol.2018.04.013
70. Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara F., Rice C., Scholes B., Sirotenko O., Howden M., McAllister T., Pan G., Romanenkov V., Schneider U., Towprayoon S., Wattenbach M. & Smith J. (2008): Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363:789-813. https://doi.org/10.1098/rstb.2007.2184
71. Smith, A. & Raven, R. (2012): What is protective space? Reconsidering niches in transitions to sustainability. Research Policy 41: 1025– 1036. https://doi.org/10.1016/j.respol.2011.12.012
72. Smolik, J.D., Dobbs, T.L. & Rickerl, D.H. (1995): The relative sustainability of alternative, conventional, and reduced-till farming systems. American Journal of Alternative Agriculture 10: 25-35. https://doi.org/10.1017/S0889189300006081
73. Tittonell, P.A. (2013): Farming Systems Ecology. Towards ecological intensification of world agriculture. Inaugural lecture. Wageningen University. https://edepot.wur.nl/258457
74. Tittonell, P.A. (2014): Ecological intensification of agriculture — sustainable by nature. Current Opinion in Environmental Sustainability 8:53-61. https://doi.org/10.1016/j.cosust.2014.08.006
75. Triboulet, P., Del Corso, J.P., Duru, M., Galliano, D., Gonçalves, A., Milou, C. & Plumecocq, G. (2019): Towards an Integrated Framework for the Governance of a Territorialised Agroecological Transition. In: Bergez JE., Audouin E., Therond O. (eds) Agroecological Transitions: From Theory to Practice in Local Participatory Design. Springer, Cham. https://doi.org/10.1007/978-3-030-01953-2_7
76. Tuck, S.L., Winqvist, C., Mota, F., Ahnström, J., Turnbull, L.A. & Bengtsson, J. (2014): Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. Journal of Applied Ecology 51:746-755. https://doi.org/10.1111/1365-2664.12219
77. UNCTAD/UNEP (2008): Organic Agriculture and food security in Africa. United Nations, New York. https://unctad.org/en/Docs/ditcted200715_en.pdf.
78. United Nations, Department of Economic and Social Affairs, Population Division (2019): World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations. https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf

79. Uphoff, N. (2007): Agroecological alternatives: capitalising on existing genetic potentials. Journal of Development Studies 43(1): 218-236. https://doi.org/10.1080/00220380601055700
80. Van der Ploeg, J.D. (2021): The political economy of agroecology. The Journal of Peasant Studies 48:274-297, https://doi.org/10.1080/03066150.2020.1725489
81. Van der Ploeg, J.D., Barjolle, D., Bruil, J., Brunori, G., Madureira, L.M.C., Dessein, J., Drąg, Z., Fink-Kessler, A., Gasselin, P., de Molina, M.G. & Gorlach, K. (2019): The economic potential of agroecology: empirical evidence from Europe. Journal of Rural Studies 71: 46–61. https://doi.org/10.1016/j.jrurstud.2019.09.003
82. Wezel, A.; Goris, M.; Bruil, J.; Félix, G.F.; Peeters, A.; Bàrberi, P.; Bellon, S. & Migliorini, P. (2018): Challenges and Action Points to Amplify Agroecology in Europe. Sustainability 10: 1598. https://doi.org/10.3390/su10051598
83. Wezel, A. (2020): Agroecological approaches and other innovations. In Herren, H., Haerlin, B. and IAASTD+10 Advisory Group (Eds.): Transformation of our Food Systems. The making of a paradigm shift. https://www.globalagriculture.org/transformation-of-our-food-systems.html
84. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L. (2019): Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. The Lancet. 393:447-492. https://doi.org/10.1016/S0140-6736(18)31788-4
85. Wood, S. & Cowie, A. (2004): A review of greenhouse gas emission factors for fertiliser production. Research and Development Division, State Forests of New South Wales. Cooperative Research Centre for Greenhouse Accounting. http://www.sciencetheearth.com/uploads/2/4/6/5/24658156/2004_wood_a_review_of_greenhouse_gas_emission_factors.pdf
86. World Resources Institute (2018): Creating a Sustainable Food Future. Synthesis Report, December 2018. https://www.wri.org/research/creating-sustainable-food-future-0

International Consortium on Applied Bioeconomy Research
ICABR

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

THE BIOECONOMY AND FOOD SYSTEMS TRANSFORMATION

by Eduardo Trigo, Hugo Chavarría, Carl Pray, Stuart J. Smyth, Agustin Torroba, Justus Wesseler, David Zilberman, Juan F. Martinez

ABOUT THE AUTHORS

Eduardo Trigo, Adviser of the Bioeconomy and Productive Development Program at the Inter-American Institute for Cooperation on Agriculture (IICA).

Hugo Chavarría, Manager of the Bioeconomy and Productive Development Program at IICA.

Carl Pray, Professor in the School of Environmental and Biological Sciences, Rutgers the State University of New Jersey.

Stuart J. Smyth, Associate Professor in the Department of Agricultural and Resource Economics at the University of Saskatchewan.

Agustin Torroba, Technical Specialist of the Bioeconomy and Productive Development Program at IICA.

Justus Wesseler, Professor and Head of the Agricultural Economics and Rural Policy Group at Wageningen University & Research.

David Zilberman, Professor in the Department of Agricultural and Resource Economics, University of California at Berkeley.

Juan F. Martinez, Consultant of the Bioeconomy and Productive Development Program at IICA.

I. BIOECONOMY CONCEPTS AND CONTRIBUTIONS

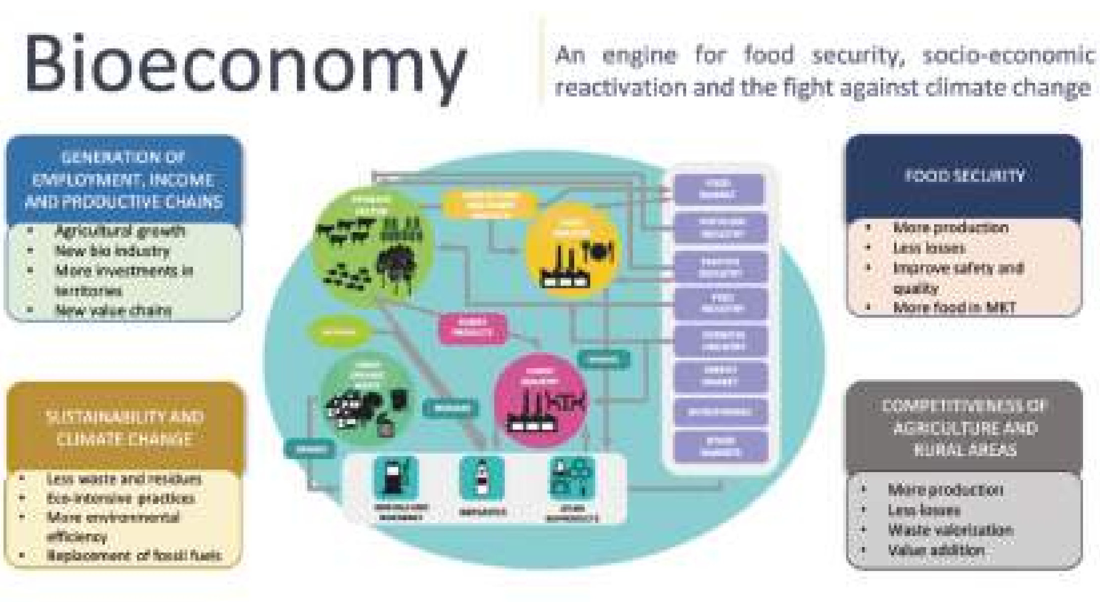
The most widely recognized definition of bioeconomy was proposed in the Global Bioeconomy Summit 2018 framework: "bioeconomy is the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy". Bioeconomy policy frameworks and development approaches make use of materials and energy found in biodiversity, biomass, and genetic resources. The knowledge generated about biological principles and processes can be replicated in new product designs.

The bioeconomy concept as a development approach is driven by advances in science and technology (S&T) and the need to address new problems and concerns. Recently, this approach has been advanced by progress in research and development in biological sciences and by complementarity and convergence with the S&T of materials (especially nanotechnology) and information (e.g. artificial intelligence (AI), digitalization, information and communication technologies (ICT), Internet of Things (IoT)). The bioeconomy concept has been favored by concerns associated with climate change, since material replacement and energy-based production processes are essential components of actions needed for adaptation and mitigation, and it is seen as an important complement to the decarbonization of the economy. Interest in the bioeconomy concept as a development approach also emerges from society's concern for meeting the increased demand for food produced more sustainably.

In addition, there are increasing changes towards sustainable consumer lifestyles, where consumers are better informed and inclined to buy environmentally friendly products. These changes create opportunities for the utilization of biomass (agricultural residuals, food waste) to increase recycling and shorten supply chains, but also as an alternative feedstock for the production of numerous materials from fuels/energy to chemicals, bioplastics, and pharmaceuticals, among others. Future bioeconomy innovations are expected to generate greater positive impacts on sustainability, like synthetic biology, novel nitrogen-fixing crops, nanofertilizers, and more.

The bioeconomy concept as a development approach has similarities and differences with concepts of the circular and green economies, which are included as approaches to sustainable development (D'Amato et al. 2017; Kardung et al. 2021). All are multidimensional concepts, having as goals the reduction of greenhouse gas (GHG) emissions, energy and material use efficiency, responsible consumption, the importance of social inclusion and the relevance of innovation. However, the bioeconomy is distinguishable by its focus on innovation and transformation of production structures, because its material and energy base are biological resources, including the use of knowledge for processing and the creation of value-added chains (Figure 1).

Figure 1 Sectors and networks of the bioeconomy



Source: Bioeconomy in Andalusia:

The bioeconomy makes important contributions to sustainable economic growth from environmental and social points of view, especially in rural areas. For example, the European Union (EU) bioeconomy (post-Brexit composition) employed ~17.5 million people, generating €614 billion of value-added production in 2017 (Ronzon et al. 2020). Furthermore, in 2017, Latin American countries like Argentina generated 2.47 million direct bioeconomy jobs (Coremberg, 2019). Nordic countries have experienced bioeconomy-related employment growth of 5-15 % (Refsgaard et al. 2021). It is estimated this development model has an economic potential of USD 7.7 trillion by 2030 (WBCSD, 2020). Previous projections are supported by trends in bioeconomy markets. While commodities like vegetable oil, sugar and cereals have growth rates of less than 4.45 %, sectors with higher value-added such as biofuels, bioplastics, and biofertilizers have grown by 25, 20 and 14 %, respectively (Betancur et al. 2018). Using new S&T to add value to biological resources leads to more profitable and sustainable markets. Cingiz et al. (2021) show the linkages between the different sectors of the bioeconomy and estimate that they contribute 30 % and 50 % to the total value-added of bioeconomy in the EU.

Finally, links between the bioeconomy and the 2030 Agenda for Sustainable Development are demonstrated by using the Sustainable Development Goals (SDGs) as indicators for bioeconomy monitoring and evaluation (Calicioglu & Bogdanski, 2021). In an analysis of national bioeconomy strategies (Linser & Lier, 2020), topics related to the SDGs were indirectly related to objectives, planned actions and proposed measurements for policy instruments aimed at promoting the bioeconomy. Fourteen relevant SDGs for the bioeconomy were identified. The bio-based economy can play a fundamental role in the decarbonization of the planet (SDG 13: Climate Action) and the production of agricultural bio-inputs, healthy food and sustainable intensification of agricultural production (SDG 2: Zero Hunger, SDG 3: Good Health and Well-Being and SDG 15: Life on Land). Additionally, the closure of production cycles through residual biomass use improves the sustainable production indicators (SDG 12: Responsible Consumption and Production and SDG 11: Sustainable Cities and Communities). Another contribution of this new paradigm is the design of biomaterials and production of different types of bioenergy (SDG 9: Industry, Innovation and Infrastructure, and SDG 7: Affordable and Clean Energy), which help to generate new jobs (SDG 8: Decent Work and Economic Growth)

The bioeconomy approach as a development model that enables achieving the SDGs related to food security and nutrition, health and well-being, and clean water and sanitation, among others, is analyzed in Table 1.

Table 1 Potential contributions of the bioeconomy to the SDGs

Potential Contribution	SDGs that contribute
Productive models that take advantage of science and technology to use biological resources sustainably and efficiently to make substitutes for petrochemicals (for example, bioenergy, biofertilizers, or bioplastics) or to satisfy new consumer demands (for example, functional foods or biocosmetics).	SDG 2: Sustainable Food Production SDG 3: Good Health and Well-Being SDG 7: Affordable and Clean Energy SDG 9: Industry and Innovation SDG 13: Climate Action
Use of productive practices that contribute to environmental sustainability and resilience while adding productivity and efficiency.	SDG 13: Climate Action SDG 15: Life on Land
Circular economy production systems, through the productive use of waste biomass derived from production and consumption processes.	SDG 11: Sustainable Cities and Communities SDG 12: Responsible Consumption and Production
Development of products, processes, and systems replicating processes and systems observed in nature.	SDG 9: Industry and Innovation SDG 14: Sustainable Use of Underwater Biodiversity SDG 15: Sustainable Use of Land Biodiversity
Bioremediation to face environmental contamination problems (for example, recovery of degraded or contaminated soils, and treatment of water for human consumption and wastewater).	SDG 6: Clean Water and Sanitation SDG 15: Prevention of Soil Degradation
Increase in the economic density of rural territories from new industrialization processes and local use of biomass for the generation of bioproducts and bio services.	SDG 8: New Sources of Decent Work and Sustainable of Economic Growth

Source: Chavarría et al. (2020).

II. BIOECONOMY CONTRIBUTIONS TO FOOD SYSTEMS TRANSFORMATION

The transformation towards more sustainable and equitable food systems (FS) seeks to provide healthy, nutritious food, while creating livelihood opportunities and reducing negative impacts. To achieve this goal, the UN Food Systems Summit has established five action tracks relating to the bioeconomy. **Action Track 1** seeks to ensure the availability of safe, nutritious food for everyone. This requires increasing crop and livestock yields through sustainable intensification activities in multifunctional landscapes, the diversification of production, and good soil management. **Action Track 2** is the shift to healthy and sustainable consumption patterns. In this case, the bioeconomy can strengthen local value chains, promoting the reuse and recycling of food resources. **Action Track 3** aims to optimize natural resources in food production, processing and distribution as pollution, soil degradation and loss of biodiversity are reduced. For this, the bioeconomy strategies focus on value chains with integrated cycles, which increase efficiency and recycling through products and co-products in different biological systems. **Action Track 4** includes strategies for integrating chains and adding value to products at the local level, contributing to poverty reduction by creating new rural jobs. **Action Track 5** promotes resilience in the face of vulnerabilities, impacts and stresses in FS. Resilience can be strengthened by a growing bioeconomy, based on the diversification of agricultural commodity production, the increased use of bio-based inputs in agriculture, and the diversification of rural incomes into rural production of bioenergy bio-based industry and environmental services. The current contingencies caused by COVID-19 and recent natural disasters highlight the importance of innovations to prepare FS for future pressures.

2.1 Advantages of Disruptive Scientific and Technological Developments

Advances in biology, ICT, and engineering are repositioning the role played by biological resources and improving our ability to understand and take full advantage of the opportunities offered. In recent decades, biology advances have accelerated with new research tools such as CRISPR-Cas9, building on new knowledge of plant, animal and microbial genomes and big data. Knowledge increases are used to increase the efficiency of crops, animals, biofuel, bioplastics and bioenergy production. They highlight the full potential of the intrinsic value of natural and biological processes. The impact of these transformative trends is augmented by the interaction among them, which is beginning to be referred to as "technological convergence". By interacting with each other, different disciplines — biology, biotechnology, chemistry, nanotechnology, data science, ICT, engineering, etc. — are driving progress in each specific field, blurring the traditional boundaries between economic sectors, changing the competitive advantages of countries and their businesses.

ICT and digitalization are important determinants of economic organization and competitiveness. Widespread connectivity, satellite technologies, data science and AI mechanisms, robotics, autonomous systems, electronic and biological sensors, virtual and augmented reality, the IoT and blockchain apps are increasing the efficiency of agriculture, food and biomass supply chains, reducing waste and resource use while increasing the quality of food and biomass. It is also becoming possible to predict climate phenomena and generate risk management programs to better deal with the consequences and monitor climate impacts, which can reduce farm management costs.

Through the use of S&T, the bioeconomy makes it possible to improve productivity and the sustainable use of biological resources by developing more productive, disease-resistant and environmentally friendly varieties of plants and animals. S&T increases biomass productivity, and develops new bioproducts with high value-added, such as nutraceuticals, bioenergy and other biological materials used by the cosmetic, pharmaceutical, chemical and other industries. Furthermore, it generates a range of new services and attaches greater value to biodiversity; for example, integrated pest management based on biological pesticides and fertilizers. It contributes to increase the efficiency of converting biological resource for food, feed, and other uses by improving biorefinery processes.

Technological convergence is a trend contributing to the renewed, modernized vision of agriculture and FS, value-added chains and international trade, especially because of young people's technological skills – which exceed those of previous generations – and the need to halt the migration of young people from rural territories to urbanized areas. These new technological scenarios are already beginning to be reflected in agriculture, agribusiness and the rural milieu, and they are increasingly perceived as offering the basis for the development of "sustainable intensification".

Supports SGDs: 3,8,9,11,12,15

2.2 Transforming Rural Environments, Generating Income and Employment Opportunities

One key bioeconomy issue is the implications of moving from fossil to bio-based value chains. Fossil raw materials are relatively homogenous, extracted in high volumes from selected productive deposits of limited area. They are transformed into products for energy sector materials, multi-stage chemical sector, and the construction sector, through large-scale industrial and logistical infrastructures. In contrast, biological carbon – biomass – comes from a highly decentralized context because the diverse nature of agriculture and forestry and "does not travel well". Due to its large volumes, limited shelf-life, and low energy and carbon density, it is not economical to transport biomass long distances before processing. Integrated biomass processing facilities need to be organized in a decentralized way, close to raw material sources.

It is these bio-based value chain characteristics that allow for significant transformations of rural landscapes and how they integrate into the economy. Bio-based value chains bring new activities into rural landscapes, diversifying income sources and the nature of existing employment opportunities. Greater economic density generates opportunities for Latin American and the Caribbean (LAC) territories, which are strongly influenced by situations of unemployment, informality (76 % of those employed), poverty (45 %; several times more than urban rates) and exclusion. The use of biomass for new industries increases economic opportunities for both agricultural and non-agricultural sectors (which in LAC generate 58 % of the income of rural territories) (ILO, 2020).

Outmigration to urban centers, aging populations and lack of youth interest to remain in farming vis-a-vis the promise of a more "attractive" future in non-agricultural jobs are common concerns in rural communities around the world. According to an OECD (2018) study that included 24 developing countries, only 45 % of rural youth are satisfied with their employment. Among the reasons for seeking a new job, rural youth mentioned a better income (36.7 %), greater stability in contracts (20 %), better working conditions (17 %) and an opportunity to increase their skills (13 %).

A second strategic component of the bioeconomy concept as a development approach and its impacts on transforming rural environments is the implications of improved energy availability to attract other economic activities beyond bio-based value chain activities. Previously, rural electrification stimulated local development processes and bioenergy options could lower costs through the decentralization of costly energy grids, improving environmental performance through the more integral use of residual biomass and waste. This is important for regions like LAC, where forest biomass is equivalent to half of its land area (and 25 % of the world's forests). Cingiz et al. (2021) show that the linkages with up- and downstream sectors makes up between 30 % to 50 % of the value-added of the bioeconomy in the EU.

Affordable, stable energy supply is a critical restriction to economic development and the bioeconomy is increasingly offering it through options that are not competitive with food production. In an increasingly interconnected world, emerging bioeconomy networks are viable strategies for reversing rural outmigration. In 2018, bioenergy generated 3.18 million jobs, equivalent to 30 % of all jobs in the renewable energy sector. Moreover, the employment generated by the biofuels sector worldwide is highly concentrated: LAC accounts for 50 % of liquid biofuel jobs worldwide, while North America accounts for 16 %.

Supports SGDs: 3,7,8,9,11,15

2.3 Improving Food Chain Resource Use

The diversification in biomass use to produce biofuels contributes to GHG reduction, generates added value and employment, and contributes to a safer, more efficient agri-food systems. Biomass fractionating results in a series of biomaterials of different added value. Biomaterials are liquid, solid and gaseous biofuels, which under the term "bioenergy" represent 10 % of the world's primary energy supply (IEA, 2019). A wide range of products linked to animal and human food (flour protein, expeller, bagasse, distillers dried/wet grains, etc.) and other high value-added products linked to the pharmaceutical, alcohol chemical and oleo chemical industries are also produced.

Biomass fractionation leads to an industry categorized as "multi-product", in which the production of co-products facilitates a better distribution in raw material production costs, making the system more efficient. Safer agri-food systems are generated, as biofuels serve as a buffer of raw materials that can be use as food in case of crisis or crop losses. The production of biofuels has generated more stable demands for raw materials, generating additional sales channels. According to Torroba (2020), 16 % of corn production worldwide, 20 % of sugar production, 19 % of soybean oil and 16 % of palm oil were destined towards biofuels. When the prices of related commodities are not attractive, the redirection of raw material derived from crops can be particularly beneficial to farmers. It generates more stable demand for raw materials, creating positive impacts on prices, and benefiting neglected LAC groups, namely family farmers, of whom 60 million work in the sector.

Biofuel productivity has improved, reflecting learning-by-doing and ongoing technological updating. Processing costs of US corn ethanol declined by 45 % between 1983 and 2010, while production volumes increased seventeen-fold, whereby learning-by-doing and economies of scale played important roles in reducing these costs. Similarly, the cost of producing sugarcane ethanol in Brazil declined by 70 % between 1975 and 2010 (Chen et al. 2015). With advances in biotechnology to enhance the productivity of feedstock plants, the efficiency of refining and the use of residue, the cost of biofuels, and their environmental impacts will decline, while their value-added is enhanced.

Supports SDGs: 7,9,13

2.4 Improved Nutrition and Health

Growing consumer interests in products with natural ingredients promotes new value chains associated with tropical biodiversity. Agroforestry systems with native fruit trees and traditional forest foods can provide the necessary macro- and micro-nutrients to improve nutrition and food security. Micro-algae possess a high nutritional value, containing protein, polyunsaturated fatty acids, bioactive carbohydrates, and antioxidants, including pigments such as carotenes, chlorophylls phycobiliproteins.

Innovations in plant breeding technologies, like those used to create genetically modified (GM) crops, have increased yields, contributing to higher household incomes, reducing poverty and enhancing household food security. Biofortified GM crops have been improving the nutritional quality of food, including increasing proteins (canola, corn, potato, rice, wheat), improving oils and fatty acids (canola, corn, rice, soy), increasing vitamin contents (potato, rice, strawberry, tomato), and increasing mineral availability (lettuce, rice, soy, corn, wheat). Nutritionally enhanced foods are preventing and/or treating leading causes of death such as cancer, diabetes, cardiovascular disease and hypertension.

In many instances, improving macro-nutrients (proteins, carbohydrates, lipids, fiber) and micro-nutrients (vitamins, minerals, functional metabolites) have significant childhood health improvements, such as reducing blindness due to the lack of vitamin availability. Improved food nutrient content, especially the increase in mineral availability, contributes to improved immunity systems and reduces stunting. In many developing countries, plant-based nutrient intake accounts for 100 % of an individual's nutrient diet, further highlighting the importance of nutritionally enhanced crop derived foods. Health benefits are extended to adulthood through reductions in cancer-causing mycotoxins, such as those found in GM corn.

One quality of life health improvement that has resulted from the small land-holder adoption of GM crops is the reduction in drudgery (Gouse et al. 2016). The majority of weed control in developing countries is done by hand labor. Hand weeding is labor commonly assigned to women. Gouse et al. (2016) found that hand weeding was reduced by three weeks over the course of a year with GM corn adoption. This allowed women to have larger vegetable gardens.

Supporting SDGs: 1,2,15

2.5 Improved Environmental Sustainability and Climate Resilience

Bioeconomy and biotechnology investments have made substantial environmental improvements, offering potential as a leading strategy in efforts to mitigate climate change. It is estimated that biomass could save 1.3 billion tons of CO2 equivalent emissions per year by providing 3,000 terawatt-hours of electricity by 2050 (Zihare et al. 2020). It is necessary to establish national instruments of measurement for GHG emissions throughout the life cycle of biofuels according to the different raw materials used to corroborate the environmental advantages. Bio-based products release fewer GHGs compared to fossil carbon commodities.

Another sustainable bioeconomy contribution is the reduction and use of food waste. In the agro-industrial sector in LAC, food waste is around 127 million tons/year, enough to satisfy the nutritional needs of 300 million people (Macias, 2020). Thanks to S&T advances, multiple technologies allow the reduction of waste and its use to produce new bioproducts (for the food, energy, chemical, pharmaceutical, and construction industries). Food waste can be considered as a cheap feedstock for producing value-added products such as biofertilizers, biofuels, biomethane, biogas, and value-added chemicals. These new industries have the potential to contribute to the mitigation objectives of climate change and the environmental sustainability of productive commercial activities due to the substitution of products of fossil origin with a high carbon footprint.

The commercialization of herbicide tolerant canola, corn and soy in the mid-1990s revolutionized land management practices, resulting in tens of millions of acres transitioning to zero-tillage. The additional commercialization of insect-resistant corn, cotton and soy has resulted in millions of fewer pesticide applications. The reduction in tillage and chemical applications has produced a significant environmental benefit, with 2.4 billion kg fewer carbon dioxide emissions and 775 million kg fewer chemical active ingredients being applied (Brookes & Barfoot, 2020). It is estimated that insect-resistant crops have reduced global pesticide use by 37 % (Klümper & Qaim, 2014). Not only are there fewer GHGs emitted during the production of crops, but the continuous cropping of fields with no tillage is increasing the soil's sequestration and storage of CO2. Conventional agricultural practices that require the use of tillage for weed control are estimated to have a net global warming potential that is 26-31 % higher than zero-tillage land (Mangalassery et al. 2014). The adoption of GM technology in corn, soybean, and cotton has reduced agricultural land and input use, saving 0.15 Gt of GHG emissions, equivalent to roughly one-eighth of the emissions from automobiles in the US (Barrows et al. 2014).

One emerging and vital area of innovative bioeconomy research is the use of innovative breeding technologies, including gene editing, to improve the abilities of plants to sequester increased amounts of carbon dioxide, allowing agricultural food production to make significant contributions to reducing the impacts of changing climates. Changes in a plant's ability to photosynthesize can have additional yield-enhancing benefits. Bioeconomy photosynthesis research that results in plants sequestering greater volumes of carbon dioxide and higher yields will ensure that crop production levels do not decline in the face of changing climates.

Plant breeding involving biotechnology and gene editing is also providing additional sustainability benefits by developing new varieties that are resistant to diseases that are threatening to destroy species. Fungal diseases and virus have had devastating impacts on the production of coffee, where an estimated 60 % of all production is threatened (Davis et al. 2019). Similar circumstances exist regarding the production of bananas, oranges and cocoa. The technology is also being applied to reintroduce species into regions where they were previously made extinct due to disease, such as the case with the American chestnut tree.

Supporting SDGs: 2,3

2.6 Upscaling Biotechnology Innovations

Humanity is facing major challenges, including climate change, food security, and rural development. The bioeconomy is poised to play a central role in addressing these challenges. New technologies in life and information sciences, combined with practical knowledge of production practices and ecosystems, can unleash the bioeconomy's potential. This requires significant investment in basic and applied research, training highly-skilled professionals, and a fluid relationship between academia and industry. Zilberman et al. (2013) suggest that the "educational industrial complex" has been essential in establishing the biotechnology and information technology sectors in the US and throughout the world. In the educational industrial complex, publicly supported basic research within universities and other research institutions leads to discoveries and innovations that are transferred to and expanded by startups and other private sector actors. Their development efforts lead to products that are produced and marketed by the private sector and transferred to final users. The educational industrial complex has already led to the establishment of supply chains for new products, including biofuels and oils, fine chemicals, pharmaceuticals and foods. University researchers have led some of these new ventures, and the exchange between universities and the private sector in clusters like the Bay Area, St. Louis, Davis, Sao Paolo, San Diego, Austin, Mendoza, Santiago, etc.

The supply chains that emerge from these industrial clusters provide direct employment in the production of technological devices and even greater opportunities in the industries resulting from these technologies. The resulting bioeconomy industries are more likely to be concentrated in rural regions, alleviating rural poverty. For example, biofuel and fine chemical production can transfer rents from owners of non-renewable resources like fossil fuels to the expanded agri-food sector. Biorefineries operate at lower temperatures, allowing for constructions smaller in size in comparison to refineries converting fossil fuels. This allows for more diversified as well as spatially-distributed scaling-up (Clomburg et al., 2017).

The success of the educational industrial complex depends on maintaining academic and research excellence. The pioneering knowledge produced by EMBRAPA was key to the emergence of Brazil as an agricultural powerhouse, suggesting that support for outstanding research institutes linked with industry is a sound social investment.

The three main obstacles to the development of the biofuels sector are regulatory uncertainty, high transaction costs, and financial constraints. Upscaling and applying new knowledge requires a science-based regulatory environment that aims to reduce regulatory burdens and accelerate the development and application of new, safe technologies. The emergence of entrepreneurial startups is more likely when venture investors and capital markets are established to support new industries and when regulatory procedures are streamlined to reduce the cost and time needed to establish the venture.

Supporting SDGs: 7,9,15

III. MOVE FORWARD

As the "activities involved in producing, processing, transporting and consuming food" (UN, 2021), FS are an integral part of the bioeconomy concept as a development approach. New developments in the biological sciences allow countries to address the many challenges that society is facing. We have summarized the many opportunities that the biological sciences have to offer. The translation of these opportunities into practice will not be trivial. There are a number of institutional factors that delay or even prevent the full exploitation of the opportunities that the bioeconomy has on offer.

First, the development of research capacity at universities and government institutes can turn these opportunities into technical and social innovations. Second, developing industries based on these innovations and the supply chains can generate employment and economic growth. Third, regulations of innovations should protect society but not disrupt the application of these opportunities in production, transportation, and consumption and unnecessarily restrict sustainable growth, jobs and resilience. The differences in regulations in different countries often reflect different societal norms and values. These institutional barriers are difficult to solve by one country alone. The UN Food Systems Summit brings together many countries and many people for discussing the removal of institutional barriers. Our overview has shown that a lot can be achieved by building research capacity and reducing institutional barriers. The impacts will be beyond the FS and affect other sectors of our economies. An open discussion will be needed that takes differences in norms and values into account without discriminating one against each other. The UN Food Systems Summit provides such an opportunity. The results depend on us.

BIBLIOGRAPHY

1. Betancur, C., Moñux, D., Canavire, G., Villanueva, D., García, J., María, L., Méndez, K., Zúñiga, A., Olaguer, E. (2018). Estudio sobre la bioeconomía como fuente de nuevas industrias basadas en el capital natural de Colombia N.°1230667, Fase I. BIOINTROPIC, Colombia.
2. Barrows, G., Sexton, S., Zilberman, D. (2014). Agricultural Biotechnology: The Promise and Prospects of Genetically Modified Crops. Journal of Economic Perspectives, 28 (1): 99–120. DOI: 10.1257/jep.28.1.99
3. Brookes, G., & Barfoot, P. (2020). Environmental impacts of genetically modified (GM) crop use 1996–2018: impacts on pesticide use and carbon emissions. GM Crops and Food, 11 (4): 215–241. https://doi.org/10.1080/21645698.2020.1773198 .
4. Calicioglu, Ö., & Bogdanski, A. (2021). Linking the bioeconomy to the 2030 sustainable development agenda: Can SDG indicators be used to monitor progress towards a sustainable bioeconomy? New Biotechnology, 61: 40–49. https://doi.org/https://doi.org/10.1016/j.nbt.2020.10.010
5. Chavarria, H., Trigo, E., Villarreal, F., Elverdin, P., Piñeiro, V. (2020). Bioeconomy: A Sustainable Development Strategy. The G20 Insights Platform, Think 20 Engagement Group. Available at https://www.g20-insights.org/policy_briefs/bioeconomy-a-sustainable-development-strategy/
6. Chen X., Nuñez H.M., Bing X. (2015). Explaining the reductions in Brazilian sugarcane ethanol production costs: importance of technological change. GCB Bioenergy, 7: 468–478 https://doi.org/10.1111/gcbb.12163
7. Cingiz, K., Gonzalez-Hermoso, H., Heijman, W., Wesseler, J. (2021). A Cross-Country Measurement of the EU Bioeconomy: An Input-Output Approach. Sustainability. Forthcoming
8. Clomburg, J., Crumbley, A., Gonzalez, R. (2017). Industrial manufacturing: the future of chemical production. Science, 355(6320):aag0804 doi: 10.1126/science.aag0804.
9. Coremberg, A. (2019). Medición de la cadena de valor de la bioeconomía en Argentina: hacia una cuenta satélite. Ministerio de Producción y Trabajo, Bolsa de Cereales, Grupo Bioeconomía. Buenos Aires.
10. D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Toppinen, A. (2017). Green, circular, bio economy: A comparative analysis of sustainability avenues. Journal of Cleaner Production, 168: 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053

11. Davis, A. P., Chadburn, H., Moat, J., O'Sullivan, R., Hargreaves, S., Nic Lughadha, E. (2019). High extinction risk for wild coffee species and implications for coffee sector sustainability. Science Advances, 5(1), 3473. DOI: 10.1126/sciadv.aav3473.
12. Gouse, M., Sengupta, D., Zambrano, P., Falck-Zepeda, J. (2016). Genetically modified maize: Less drudgery for her, more maize for him? World Development, 83: 27–38. http://dx.doi.org/10.1016/j.worlddev.2016.03.008.
13. Hassan, S., Williams, G. A., Jaiswal, A. K. (2018). Emerging technologies for the pretreatment of lignocellulosic biomass. Bioresource Technology, 262: 310–318. https://doi.org/https://doi.org/10.1016/j.biortech.2018.04.099
14. IEA. (2019). World Energy Balances 2019 (online). Paris, France. Retrieved 21 Jan. 2020.
15. ILO. (2020). Sector rural y desarrollo local en América Latina y el Caribe. https://www.ilo.org/americas/temas/sector-rural-y-desarrollo-local/lang--es/index.htm (Assessed February 14).
16. Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., van Leeuwen, M., M'Barek, R., van Meijl, H., Piotrowski, S., Ronzon, T., Sauer, J., Verhoog, D., Verkerk, P.J., Vrachioli, M., Wesseler, J.H.H., Zhu, B.X. (2020). Development of the Circular Bioeconomy: Drivers and Indicators. Sustainability, 13 (1): 413. https://doi.org/10.3390/su13010413
17. Klümper, W., & Qaim, M. (2014). A meta- analysis of the impacts of genetically modified crops. PLoS ONE, 9: 1–7. https://doi.org/10.1371/journal.pone.0111629.
18. Linser, S., & Lier, M. (2020). The contribution of Sustainable Development Goals and forest-related indicators to national bioeconomy progress monitoring. Sustainability, 12 (7): 2898 https://doi.org/10.3390/su12072898
19. Macias, M., Girón, C., Nieto M., Chavrier, N., Páez, D., Ureña, M., Moreno, J., García M., de la ViñHassan, S. S., Williams, G. A., Jaiswal, A. K. (2018). Emerging technologies for the pretreatment of lignocellulosic biomass. Bioresource Technology, 262: 310–318. https://doi.org/https://doi.org/10.1016/j.biortech.2018.04.099
20. Mangalassery, S., Sjögersten, S., Sparkes, D. L., Sturrock, C. J., Craigon, J., Mooney, S. J. (2014). To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? Scientific Reports, 4: 4586. https://doi.org/10.1038/srep04586.
21. OECD. (2018). The Future of Rural Youth in Developing Countries: Tapping the Potential of Local Value Chains, OECD Publishing, Paris, https://doi.org/10.1787/9789264298521-en.
22. Refsgaard, K., Kull, M., Slätmo, E., & Meijer, M. W. (2021). Bioeconomy – A driver for regional development in the Nordic countries. New Biotechnology, 60: 130–137. https://doi.org/https://doi.org/10.1016/j.nbt.2020.10.001
23. Ronzon, T., Piotrowski, S., Tamosiunas, S., Dammer, L., Carus, M., M'barek, R. (2020). Developments of Economic Growth and Employment in Bioeconomy Sectors across the EU. Sustainability, 12,11:4507. https://doi.org/10.3390/su12114507
24. Torroba, A. (2020). Atlas de los biocombustibles líquidos 2019-2020. San José, Costa Rica. https://repositorio.iica.int/bitstream/handle/11324/13974/BVE20128304e.pdf?sequence=1&isAllowed=y
25. United Nations. (2021). Food Systems Summit 2021. https://www.un.org/en/food-systems-summit/about. (Assessed February 14, 2021).
26. WBCSD (2020). The circular bioeconomy: A business opportunity contributing to a sustainable world. https://www.wbcsd.org/Programs/Circular-Economy/Factor-10/Resources/The-circular-bioeconomy-A-business-opportunity-contributing-to-a-sustainable-world?fbclid=IwAR0qdYD0UCczuTvzV3YhSqhxkllAu6ftnvbR7kQ1ee758pT4S_cn_iLg7e0
27. Wesseler, J. & Joachim von Braun. (2017). Measuring the Bioeconomy: Economics and Policies. Annual Review of Resource Economics. Annu. Rev. Resour. Econ., 9: 275–298
28. Wesseler, J., Smart, R., Thomson, J., Zilberman, D. (2017). Foregone benefits of important food crop improvements in Sub-Saharan Africa. PLoS ONE, 12(7), e0181353.
29. Zihare, L., Muizniece, I., Spalvins, K., & Blumberga, D. (2018). Analytical framework for commercialization of the innovation: case of thermal packaging material. Energy Procedia, 147:374–381. https://doi.org/10.1016/j.egypro.2018.07.106
30. Zilberman, D., Kim, E., Kirschner, S., Kaplan, S., Reeves, J. (2013). Technology and the future bioeconomy. Agricultural Economics, 44: 95-102. https://doi.org/10.1111/agec.12054

Global Panel on Agriculture and Food Systems for Nutrition

UNITED NATIONS FOOD SYSTEMS SUMMIT 2021
The Scientific Group for the UN Food System Summit
sc-fss2021.org

Food Systems Summit Brief
prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

THE TRANSITION STEPS NEEDED TO TRANSFORM OUR FOOD SYSTEMS

by Patrick Webb, Derek J. Flynn, Niamh M. Kelly, and Sandy M. Thomas
on behalf of the Global Panel on Agriculture and Food Systems for Nutrition

1. INTRODUCTION

The United Nations (UN) Food Systems Summit and N4G meetings in 2021 reflect a growing international recognition that the policies that fed the world in the twentieth century are no longer fit for purpose. Urgent reform is essential to achieve the goal of universally accessible and affordable healthy diets delivered by food systems that are environmentally, economically, and socially sustainable.

Today's food systems are asked to nourish the world's growing population in ways that do no harm to either human or planetary health. However, the growing problems facing food systems now amount to a two-fold crisis. First, global progress in addressing malnutrition in all its forms (including undernutrition, obesity, and micronutrient deficiencies) and reducing diet-related diseases has stalled. Food systems are failing to provide affordable healthy diets for three billion people.[1] This affects their health, the mental and physical

ABOUT THE AUTHORS

Patrick Webb, Professor, Tufts University; Technical Adviser to the Global Panel

Derek J. Flynn, Consultant to the Global Panel

Niamh M. Kelly, Policy Research Officer at the Global Panel

Sandy M. Thomas,Director of the Global Panel Secretariat

development of children, and the earning potential of those children throughout their lives. Those affected risk being locked into lifelong inequality. Second, food systems are in a spiral of decline with environmental systems:[2] they are a major cause of worsening degradation of soil, water and air quality, biodiversity loss and climate change. Moreover, although food systems have generally responded to the challenges posed by COVID-19, the pandemic has highlighted just how fragile and precarious the world's food systems have become.

Without decisive action, the situation is set to worsen in the future due to a multitude of factors: population growth and climate change, increasing competition for land, water, and other natural resources, and emerging diseases, conflict, and economic volatility. The stakes could not be higher, not just for the health of the world's population and the planet, but also for the delivery of most of the Sustainable Development Goals (SDGs), such as those relating to hunger and nutrition, growth, equality, education, wellbeing, and sustainable cities and communities.[3]

Minor adjustments on the margins of today's food systems will be inadequate. All stakeholders involved in food systems, including government policy-makers, donors, businesses, non-governmental organisations, and civil society, should be encouraged to adopt a much more radical approach. They need to rethink the ways in which food systems are currently managed, governed, and used, and at the most fundamental level they must decide what food systems need to deliver and how the performance of those systems is assessed. Reshaping food systems to respond simultaneously to nutritional, health, economic, and environmental challenges presents considerable challenges but also great opportunities for actions that would yield considerable benefits to countries (see Box 1).

However, it is not enough merely to have a vision for future transformed food systems. Policy-makers need to chart a way forward to achieve them through a practical and pragmatic plan for the specific transition steps that need to be taken, and how they would be funded, implemented, and managed. Developing such a plan, and implementing it effectively, presents massive challenges that must cut through the complexity of food systems and competing priorities. It will need to navigate a path through powerful forces and vested interests that might favour the status quo and impede policy change. It must also be affordable at a time when countries are still grappling with the economic catastrophe of COVID-19. The transition needs to be viewed with realism, rather than being an abstract ideal. Against this background, the following sections of this paper set out the steps of the transition process that need to be taken on the road to a fundamental transformation of food systems.

Box 1. The potential benefits of transformed food systems

Sustainable healthy diets that are accessible and affordable for all would help to drive much-needed progress across most of the SDGs. Potential benefits include:

- Elimination of a major cause of inequality for the three billion people who today cannot access a healthy diet.[5,6]
- A substantial reduction in levels of stunting, which in 2019 affected 144 million children under five years, and wasting, which affects 47 million pre-school children. This would lead to benefits in terms of cognitive development and educational attainment for children, and a more productive workforce.
- A substantial reduction in the prevalence of diet-related non-communicable diseases (NCDs). Without action, health costs linked to mortality and the health impacts of NCDs could reach US$2.5 trillion per year globally by 2030.[5]
- A reduction of 41-74 % in food system greenhouse gas emissions, while boosting resilience to climate shocks. This would also greatly contribute to addressing biodiversity loss. Agriculture is the largest contributor to the latter – the global annual loss of pollinating insects alone is estimated to cost US$235-577 billion.[6]
- A substantial reduction in the economic drag presented by inadequate nutrition, which ranges from 2 % to 3 % of GDP in some countries and up to 11 % of GDP in Africa and Asia each year. This would engender progress on poverty reduction, education, and equality.[7]

1.1 What the transition process needs to achieve

A series of steps must be urgently planned, discussed, financed, and enacted to allow the world's food systems to transition from their current sub-optimal state to one where they fully support the dietary patterns needed to maximise human and planetary health. The following are five key outcomes that broadly map onto the original UN Food Systems Summit Action Tracks and could usefully be considered within the Summit's deliberations.

- Food systems need to move beyond addressing hunger to address all forms of malnutrition. They need to deliver universal access to healthy diets. This means addressing all forms of malnutrition, in part by ensuring improved diets for all. Nonetheless, there is a global shortfall in the production of the range of nutrient-rich foods required to provide healthy diets for everyone. For example, only 34 % of fruits and vegetables needed for everyone to access a healthy diet are being produced.4 Healthy diets are currently also unaffordable for three billion people worldwide.
- Consumer demand needs to be harnessed as a significant driver of change. Consumers must be able to make informed choices and be encouraged to select nutrient-rich food options, and to play their part in reducing waste. The latter is especially important in view of projected increases in the global population, combined with increasing stresses in environmental systems essential for food production such as land, soils, and water.
- Food systems must become fully environmentally sustainable, thereby operating within planetary boundaries. This is one of the three 'pillars' of the SDGs and it is essential for both the future health of the planet and the future viability of food systems to nourish the world. Policy-makers need to adopt a perspective that considers the environmental footprint of all parts of food systems, from farm to fork. This perspective needs to encompass greenhouse gas emissions, as well as the effect of food systems on biodiversity loss, changing land use and deforestation, water use, and more besides. Substantial reduction in losses throughout the food chain, of foods and the nutrients that they contain, needs to be a priority.
- The transition needs to be a 'just' rural and urban process so that it reduces inequality and inequities of all kinds, rather than increasing them. No one must be left behind.
- The transition needs to deliver transformed food systems capable of operating at two speeds, i.e. responding to immediate needs and short-term shocks, but also able to address the long-term restructuring of food systems needed to respond to climate change, population growth, and urbanisation. Governments have been too slow to act on climate change and biodiversity loss, despite warnings over many years. More recently, COVID-19 has exposed the profound fragility of food systems, and their potential to exacerbate instability and conflict; for example, through food riots.

2. PLANNING THE TRANSITION STEPS

Food systems are complex, dynamic, and comprise many different interacting subsystems, but food system policies often fail to recognise this. Too often a narrow approach is adopted that focuses on specific parts of the food system; for example, when setting production targets for specific food commodities. The reality is that the diverse parts of food systems are in constant flux, with the many parts influencing each other in a web of relationships. Production, trade, food prices and consumer demand are notable examples. Policy-makers need to think in terms of food systems as a whole and as interacting dynamic systems rather than individual isolated components in equilibrium.

The choice of initial transition steps should be informed by a comprehensive analysis of existing policies and private sector investments, to help identify priority outcomes (defined in holistic human and planetary dimensions), and barriers to change. A food system assessment of all public funding and institutional mandates can distinguish those that could be repurposed to help cover the costs of transition phase actions. Similarly, a review of existing food system functions, challenges and benefits would determine where best to target actions to increase the availability of nutrient-rich foods in particular, and to improve the efficiency of food value chains overall.

The complexity of food systems presents a challenge for policy-makers trying to decide the first steps of the transition process. This is because of the myriad possible actions, policies and interventions. The following subsections outline how the necessary choices may be navigated.

2.1 New priorities and principles to guide transition choices

New metrics of 'success' in the process of food system transition are needed to frame and monitor policy decisions. For example, the failure to properly account for the value of human health and the natural environment in policy decisions relating to food systems is both a market failure and a widespread institutional failure. Unless addressed at the outset, this fundamental flaw will continue to distort or impede progress in food system transition.

More generally, decisions involved in planning the transition of food systems will require a new approach that should adhere to the following principles: at every stage of the transition ensure inequality does not increase, and that the poor are able to access and afford healthy diets; avoid closing off options for the future; invest in strengthening institutions and capacity building; ensure transparency to engender trust and 'buy-in'; base decisions on evidence and transparent expectations; and establish feedback mechanisms for adjustment. This last point is particularly relevant to actions that may be under-explored in some contexts. Limited trials of different options with wide societal engagement and transparency of intent will help to start the transition process, and inform subsequent wider rollouts.

A priority should be to ensure a 'just' transition where all classes of society benefit, and where inequality at all scales (international, national, and local) is reduced rather than increased. This is important since low- and middle-income countries (LMICs) are likely to be least able to resource the transition of their food systems, and the poor in any country will be inadequately placed to cope with fluctuations in food prices that might occur during the process. Coordination between high-income countries (HICs), LMICs and the donor community will be needed to support transition agendas.

Policy decisions across government also need to be aligned with national food-based dietary guidelines (FBDGs). FBDGs are now available in roughly 100 countries across the world and are designed to inform consumer choice.8 However, much greater use should be made of them to inform policy decisions in all relevant areas of government, from trade to infrastructure development, health and the environment. Without this common approach, different parts of government risk pulling in different directions, rather than working together towards a common agenda of food system transition. FBDGs also need to be reassessed and updated to reflect the latest science, and to embody issues of sustainability as well as dietary health.

2.2 Placing poor and marginalised people at the heart of the transition

The transition of food systems has the potential to address societal inequalities in several ways. By ensuring access to diets that are affordable, healthy and sustainable, it has immediate benefit for the three billion who cannot afford healthy diets today.1 At a stroke, access to healthy diets for pregnant women and children will address the lifetime inequalities relating to health and mental development that malnutrition can cause. Consequential increases in productivity and lifetime earnings would further help to lift families out of poverty, thereby helping to open up wider opportunities.

However, a key challenge for policy-makers is to ensure that the transition reduces inequality rather than increasing it. At the country level, the latter is a real threat: LMICs are likely to be less able to resource the necessary transition steps, and thus they risk falling further behind HICs. For individual families, the poorest will be least able to afford nutrient-rich food alternatives if they are more expensive, and less able to cope with fluctuations in food prices that might occur as food systems change. The effects of the transition of jobs and livelihoods needs to be managed particularly carefully, recognising the vital importance of the food sector as a major source of employment for the poor across the world.

If the transition of food systems is to reduce inequality, then policy-makers must commit to specific actions at both international and national levels:

- Disruption to trade in general, and through protectionism in particular, must be avoided. Trade is a vital tool to minimise food prices and maintain food security, particularly at times of stress and price volatility.
- Governments need to promote growth that is specifically inclusive and pro-poor. This is a vital component in a strategy to address affordability.
- Donors need to specifically focus their attention on protecting the poor from price fluctuations that may occur during the transition.
  Planning the transition of their food systems is likely to be a particular challenge for those LMICs that are heavily resource constrained. It is suggested that governments in LMICs should give particular consideration to the following:
- Repurposing existing expenditure across government, recognising that sustainable healthy diets can contribute to multiple policy agendas, including health, economic growth, and education.
- Giving particular focus to actions that are, to first order, cost neutral; for example, rebalancing production (terrestrial and aquatic food systems of all kinds) subsidies and research, taxes and regulation. Influencing consumer dietary choices is potentially low cost but has considerable potential to drive change throughout food systems.
- Leveraging the considerable resources of the private sector by forging a partnership to work together on a common agenda.
- Focusing attention on actions that simultaneously produce multiple wins.

- Using reviews to prioritise where to focus actions within food systems, and using the best science, evidence, and modelling to help choose the most cost-effective actions.

2.3 Tackling trade-offs and compromises head on

The need to resolve competing policy and investment priorities operates at many scales and contexts. It is a daily reality in governments when resources are constrained and actions need to be prioritised, in private companies when making investment choices on product portfolios or retail strategies, and in households when making day-to-day food-purchase choices.[9–11]

Policy-makers seeking to transition food systems need to think through how to navigate difficult trade-offs that may lie entirely within the food system, but equally may involve wider areas of policy. Examples include how to balance resource expenditure between education, stimulating economic growth, and investing specifically in food systems, how to allocate scarce resources between addressing different forms of malnutrition which may affect a population simultaneously including undernutrition, micronutrient deficiencies, or overweight and obesity, how to strike a balance between investing in agriculture and fisheries versus other sectors in rural communities, and how to balance avoiding coronavirus-led debt default in the short-term with investing in food system transition to achieve longer-term health and economic benefits.

Trade-offs may usefully be approached through mapping out existing policies in relation to new goals and likely trade-offs, developing a clear understanding of the costs and benefits of alternative actions, transparently defining who pays and benefits from alternative strategies, taking a longer-term perspective, and ensuring affordability as a priority.[1,12]

2.4 Ensuring that the transition process is appropriately resourced

The transition of food systems will inevitably incur costs before the benefits can be realised. These costs will likely manifest in all domains of the system, from production through to trade, food processing, retail, and consumption. It is therefore necessary that the distribution and impacts of these costs are identified, understood, and managed effectively. Put simply, it is essential to have clarity from the outset about how the transition steps would be resourced. This will be doubly important not only to ensure that reform can move beyond political aspiration, but also so that the transition does not further widen the gap between HICs and LMICs. Much can be achieved by repurposing (see Section 4) or refocusing existing resources (for example, shifting subsidies and realigning taxes and incentives), and through negotiating more equitable trade agreements. Identifying actions that produce multiple benefits (win-wins) may also help. However, the following non-governmental also need to be considered:

- **Incentivise the private sector to realign its resources to help support national agendas of delivering healthier diets in a sustainable manner.** The public sector cannot deliver transformed food systems on its own; rather, it needs to work in partnership with the private sector. However, many commercial actors too often act in ways that are not conducive to health or to the sustainability of food systems. This is incompatible with the necessary transition agenda and needs to change. It is important for governments to incentivise businesses to make a much wider range of nutrient-rich foods affordable to the entirety of ‘bottom of the pyramid’ families. More generally, a comprehensive framework for food industry engagement needs to be established.
- **Establish a dedicated global financing facility for a food systems transition.** Such a facility would mobilise multilateral resources to support and incentivise increased allocations of domestic resources towards making food systems more resilient and diets both more sustainable and healthier. A particular priority for such a facility would be to assist LMICs in their transition, recognising the severe financial constraints in which many operate. It also has the potential to catalyse reform where there is a mismatch between the actors who need to resource change, and those who stand to benefit.
- **Realign donor policies towards supporting actions that promote the achievement of both human health and planetary goals.** A particular priority should be the protection of the poor during the transition by refocusing social protection policies so that the poor will be able to cope with fluctuations in the availability and price of foods that may occur during this time.

3. INCENTIVISING AND SUPPORTING ACTIONS

Given the diverse benefits that would result from achieving sustainable, healthy diets for all, the limited actions taken by countries across the world in recent decades[2] represent a huge missed opportunity. The reasons for this are many and varied but include insufficient policy focus by governments on improving diet quality and nutrient-rich foods (as opposed to the provision of staples).

A further issue concerns the private sector. Despite playing a major role in feeding the world, the private sector too often develops and promotes foods that are not conducive to healthy diets, or which rely on food production systems that over-exploit natural resources. The benefits mainly accrue to private sector stakeholders, while the costs (population-wide ill health, ecological degradation, etc.) are mainly borne by the public sector and wider society. This mismatch has impeded progress in the past and must be addressed as part of the transition.

Many factors also affect the pace of change. Global food systems involve powerful business interests with considerable investment in the status quo: revenues of the global food system are estimated to reach US$8 trillion in 2021.[13,14] The implementation of policy change may also be constrained by limited resources, particularly in LMICs, and especially in a post-COVID-19 world. Major shifts in policy may incur political risks, and decision-makers typically assign more weight to these compared with the risks associated with maintaining the status quo.[7] Moreover, at the level of the consumer, dietary choices may be heavily conditioned by evolving cultural or religious norms.[15,16] However, three systemic issues stand out within the policy environment. Addressing these at the outset of the transition is essential.

3.1 The misalignment between the complexity and interconnectedness of food and environmental systems, and how they are managed today

Policy actions on food, health, agriculture and fisheries, and climate are typically managed in isolation, in an organisational approach that is inherently unsuited to managing complex food systems. The need for 'joined up' policy is a cliché but remains widely relevant. This important issue can be addressed through a combination of measures: training and sensitisation of policy leads in all relevant sectors to the urgency of the transition, leadership at the highest levels in government, convincing relevant policy-makers across government of the critical importance of sustainable, healthy diets to their respective policy agendas, embedding these objectives into their own plans and strategies so that all parts of government drive change within a common transition agenda, and establishing targets for actions that improve food system functions in ways that deliver multiple benefits simultaneously.

3.2 Inadequacies in science and evidence for policy development

Trusted, high-quality science and evidence are essential to give policy-makers the confidence to take the bold decisions that are required. There is a need to address major gaps in the evidence base, particularly in LMICs where evidence of 'what works' is often limited, establish a common science base that is recognised as independent, widely trusted, and freely available to all countries, and develop consensus around contentious areas of policy.

The idea for a creation of an IPCC-like organisation for sustainable food systems (an 'International Panel for Food System Science', or IPFSS) has been mooted in recent years and offers one way to help deliver the necessary improvements. This idea is now gathering support from major stakeholders.

An important role of the IPFSS would be to engender trust in the science and evidence in two distinct communities. In the case of policy-makers, it would engender confidence and provide support in justifying difficult or controversial decisions. However, trust in the underlying science is equally critical for citizens who can exert considerable influence throughout the food system through their individual and collective food choices.[2] Misinformation circulating on the internet and social media concerning climate change, and now vaccinations, all illustrate how false information can dangerously mislead consumers.

3.3 Metrics for monitoring, tracking, and adjusting the transition process

Effectively measuring what policy-makers and businesses manage is key to identifying what works and what is most cost-effective, as well as for supporting transparency and accountability.[17] As such, the transition steps in food system reform must be carefully based on appropriate evidence where it is available,[18] and should promote making evidence available where it is not.[2] For example, it remains difficult to compare diets (what people actually eat) across geographies and over time. This gap in appropriate measurement and monitoring continues to impair the prospect of reaching a global consensus on what elements should be included to define healthy or high-quality diets, and how to ensure the planetary sustainability of the food systems that underpin them.

What is urgently needed is open-access portals for data not just on diets, but on all elements of food system functions, including information access, market prices, and the nature and quality of food environments, all of which are needed in forms that can be effectively linked with global trade and climate change models to better inform policy choices.

4. WHO NEEDS TO ACT: PRIORITIES FOR TRANSITIONING FOOD SYSTEMS TO PROTECT HUMAN AND PLANETARY HEALTH

The transition of food systems requires global leadership with a long-term focus and the delivery of a coherent set of commitments and actions that place both people's and the planet's health at the centre. For the next decade, the structure of the SDGs will help to provide a coherent framework for action. Global leadership, such as that expected to emerge more fully from the UN Food Systems Summit, will help to provide the continuity needed as well as mechanisms for periodic reassessment and reorientation.

However, global leadership must be supplemented with and supported by national, regional, and local level initiatives that bring together public, private, and civil society actors around the priorities that are most urgent, feasible, and essential for food system transformation. The Global Panel's recent Foresight report sets out detailed recommendations for different classes of stakeholder, and different parts of the food system, recognising that such actions will usually need to be tailored to individual circumstances. However, the following priorities are generally applicable:

International:

1. **Leaders and decision-makers should capitalise upon upcoming global fora to agree to new commitments for making food systems more resilient and diets that are healthy and sustainable.** Both the Nutrition for Growth (N4G) Summit and the UN Food Systems Summit are important opportunities to explore the creation of a dedicated global financing facility for food systems transformation and secure national endorsements for change, including much improved capacity for research and evidence to better support policy decisions. A new vision for sustainable food systems delivering healthy diets for all must be supported through the best science and evidence of what works as informed by practical evidence.
2. **Policy-makers must build on existing global development targets (such as the SDGs and the Paris Agreement on Climate Change) so they embody the goal of sustainable, healthy diets for everyone as a shared objective.** These targets need to recognise the central importance of sustainable, healthy diets as a key enabler for progress on diverse agendas; for example, relating to inequality, economic growth, climate change, environmental degradation, and livelihoods and job creation.

Governments:

3. **Food systems and the policies that govern them need to be people-centred.** This means ensuring that healthy diets are available to all people irrespective of class, religion, gender and age. It means recognising the vital role that food systems play in providing livelihoods for countless millions, particularly for poor and marginalised groups. Moreover, it means ensuring that policy-makers understand and recognise the central importance of healthy diets for physical and mental development, as a foundation for health, prosperity and wellbeing.
4. **Policy-makers in relevant government departments must address planetary and dietary challenges simultaneously because they are fundamentally interlinked**. The approach to date, where these issues were tackled piecemeal and in silos, simply will not work.
5. **Governments in countries at all stages of development must resolve policy distortions which could fundamentally impede change, or even drive food systems in the wrong direction.** Examples include taxation and regulation, subsidies, and food-related research and development. The aim is to give much greater weight to the importance of nutrient-rich foods and better support measures that further both human and planetary health simultaneously.
6. **Relevant ministries (e.g. agriculture, fisheries, health, transport infrastructure, environment) need to work together to implement policies to realign production systems so that they support healthy diets in sustainable ways.** Food systems today do not produce enough nutrient-rich foods to meet today's needs, let alone projected demand over coming decades, nor are they producing most foods sustainably. Narrow targets relating to productivity need to be replaced with broader measures valuing efficiency and sustainability.
7. **Relevant government departments need to prioritise building the resilience of food systems, as COVID-19 has highlighted their current deficiencies and vulnerabilities.**[3] A broad approach is required that addresses the causes of the lack of

resilience within food systems, the root causes of the threats, and mitigation measures that may be needed during times of stress.

8. **Governments in all countries should creatively target actions that can create multiple 'wins' across health and sustainability.** Opportunities need to be sought throughout food systems, from farm to fork. Major projects in sub-Saharan Africa and China have already shown that this is possible, creating substantial and lasting benefits in terms of jobs, equality, and the development and prosperity of individuals and regions.[19–22] Technology innovations across food systems from production through processing, storage, and retail hold considerable promise.

Donors:

9. **Donor agencies must support LMICs to ensure that the transition of food systems is socially and ethically just.** They have an important role to play to ensure that the poorest are protected during and after a period of food system transition.

Companies operating in the food system:

10. **Major transnational businesses and local SMEs must work closely with governments on more clearly articulated common agendas to deliver sustainable, healthy diets.** A comprehensive framework for food industry engagement is needed: it is essential that the public and private sectors work together on common agendas and share the costs of implementing them. The private sector must spell out specific, measurable responsibilities for improving diet quality and the sustainability of food systems and be willingly held accountable.

Civil society:

11. **Civil society advocacy groups and citizens need to play their part. The former have a major role in leveraging change in businesses operating across food systems and holding policy-makers to account, and the latter have considerable influence to drive change through their purchasing power.** However, shifts in demand in favour of sustainable, healthy diets will need encouragement and empowerment through information from trusted sources.

REFERENCES

1. FAO, IFAD, UNICED, WFP W. The State of Food Security and Nutrition in the World: Transforming Food Systems for Affordable Healthy Diets. Rome, Italy; 2020.
2. Global Panel on Agriculture and Food Systems for Nutrition. Future Food Systems: For people, our planet, and prosperity. London, UK; 2020.
3. Global Panel on Agriculture and Food Systems for Nutrition. Healthy diets for all: A key to meeting the SDGs. Policy Brief No. 10. London, UK; 2017.
4. KC KB, Dias GM, Veeramani A, Swanton CJ, Fraser D, Steinke D, et al. When too much isn't enough: Does current food production meet global nutritional needs? PLoS One. 2018.13(10).
5. Bommer C, Sagalova V, Heesemann E, Manne-Goehler J, Atun R, Bärnighausen T, et al. Global Economic Burden of Diabetes in Adults: Projections From 2015 to 2030. Diabetes Care. 2018.41(5):963–70.
6. IPBES. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Population and Development Review. Bonn, Germany; 2019.
7. The World Bank and Nutrition. 2019; Available from: https://www.worldbank.org/en/topic/nutrition/overview
8. FAO. Home | Food-based dietary guidelines | Food and Agriculture Organization of the United Nations. Available from: http://www.fao.org/nutrition/education/food-dietary-guidelines/en/
9. Global Panel on Agriculture and Food Systems for Nutrition. Rethinking Trade Policies to Support Healthier Diets. Policy Brief. London, UK; 2020.
10. Webb P. Medium- to Long-Run Implications of High Food Prices for Global Nutrition. J Nutr. 2010.140(1):143S-147S. Available from: https://doi.org/10.3945/jn.109.110536
11. Global Panel on Agriculture and Food Systems for Nutrition. Urban diets and nutrition: Trends, challenges and opportunities for policy action. Vol. 9. London, UK; 2017.
12. Herforth A, Bai Y, Venkat A, Mahrt K, Ebel A, Masters WA. Cost and affordability of healthy diets across countries. Technical Background Paper for SOFI 2020: The State of Food Security and Nutrition in the World, 2020. 2020.
13. Statista. Food - Worldwide | Statista Market Forecast. 2020; Available from: https://www.statista.com/outlook/cmo/food/worldwide

14. Van Nieuwkoop M. Do the costs of the global food system outweigh its monetary value? World Bank. 2019; Available from: https://blogs.worldbank.org/voices/do-costs-global-food-system-outweigh-its-monetary-value
15. Monterrosa EC, Frongillo EA, Drewnowski A, de Pee S, Vandevijvere S. Sociocultural Influences on Food Choices and Implications for Sustainable Healthy Diets. Food Nutr Bull. 2020.41. Available from: https://doi.org/10.1177/0379572120975874
16. Alonso S, Aderu S, Bekele TH, Bishaw Z, Brouwer ID, Brown LR, et al. Background paper. Transforming Ethiopian Food Systems: Better diet quality, prosperity, and sustainability in a changing climate. 2021.
17. The World Bank. World Development Report 2021: Data for Better Lives. A World Bank Flagship Report. Washington, DC; 2021.
18. International Food Policy Research Institute. 2021 Global Food Policy Report: Transforming Food Systems after COVID-19. Washington, DC; 2021.
19. Fu B, Liu Y, Lü Y, He C, Zeng Y, Wu B. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecol Complex. 2011.8(4):284–93.
20. Lü Y, Fu B, Feng X, Zeng Y, Liu Y, Chang R, et al. A Policy-Driven Large Scale Ecological Restoration: Quantifying Ecosystem Services Changes in the Loess Plateau of China. PLoS One. 2012.7(2).
21. Deng X. Restoration and Development of the Degraded Loess Plateau, China. 2014. 215–231 p.
22. Goffner D, Sinare H, Gordon LJ. The Great Green Wall for the Sahara and the Sahel Initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. Reg Environ Chang. 2019.19(5):1417–28.

ANNEX 1: THE FOOD SYSTEMS SUMMIT BRIEFS BY PARTNERS OF THE SCIENTIFIC GROUP

A. Modelling and Strategizing Food Systems Transformations

The Bioeconomy and Food Systems Transformation
by Eduardo Trigo, Hugo Chavarria, Carl Pray, Stuart J. Smyth, Agustin Torroba, Justus Wesseler, David Zilberman, Juan F. Martinez (February 17, 2021)
doi.org/10.48565/scfss2021-w513

The Transition Steps Needed to Transform Our Food Systems
by Patrick Webb, Derek J. Flynn, Niamh M. Kelly, and Sandy M. Thomas on behalf of the Global Panel on Agriculture and Food Systems for Nutrition (April 26, 2021)
doi.org/10.48565/scfss2021-hz63

Cost and Affordability of Preparing a Basic Meal around the World
by William A. Masters, Elena M. Martinez, Friederike Greb, Anna Herforth, Sheryl L. Hendriks (May 2021)
https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Cost_of_Basic_Meals.pdf

B. Science, Technology, and Innovation Actions

The Role of Science, Technology and Innovation for Transforming Food Systems Globally
by Robin Fears, Claudia Canales (April 2021)
doi.org/10.48565/scfss2021-q703

How could science–policy interfaces boost food system transformation?
by Etienne Hainzelin, Patrick Caron, Frank Place, Arlène Alpha, Sandrine Dury, Ruben Echeverria, Amanda Harding (May 14, 2021)
doi.org/10.48565/scfss2021-4y32

Food System Innovations and Digital Technologies to Foster Productivity Growth and Rural Transformation
by Rui Benfica, Judith Chambers, Jawoo Koo, Alejandro Nin-Pratt, José Falck-Zepeda, Gert-Jan Stads, Channing Arndt (May 2021)
doi.org/10.48565/scfss2021-6180

Leveraging data, models & farming innovation to prevent, prepare for & manage pest incursions: Delivering a pest risk service for low-income countries
by Taylor, B; Tonnang, HEZ; Beale, T; Holland, W; Oronje, M; Abdel-Rahman, EM; Onyango, D., Finegold, C; Zhu, J; Pozzi, S, Murphy, ST (April 15, 2021)
doi.org/10.48565/scfss2021-ty56

Food Systems Innovation Hubs in Low-and-Middle-Income Countries
by Kalpana Beesabathuni, Sufia Askari, Madhavika Bajoria, Martin Bloem, Breda Gavin-Smith, Hamid Hamirani, Klaus Kraemer, Priyanka Kumari, Srujith Lingala, Anne Milan, Puja Tshering, Kesso Gabrielle van Zutphen, Kris Woltering (March 26, 2021)
doi.org/10.48565/scfss2021-fh72

A New Paradigm for Plant Nutrition
by Achim Dobermann, Tom Bruulsema, Ismail Cakmak, Bruno Gerard, Kaushik Majumdar, Michael McLaughlin, Pytrik Reidsma, Bernard Vanlauwe, Lini Wollenberg, Fusuo Zhang, Xin Zhang (February 10, 2021)
doi.org/10.48565/SCFSS2021-HG55

A Whole Earth Approach to Nature Positive Food: Biodiversity and Agriculture
by Fabrice A.J. DeClerck, Izabella Koziell, Tim Benton, Lucas A. Garibaldi, Claire Kremen, Martine Maron, Cristina Rumbaitis Del Rio, Aman Sidhu, Jonathan Wirths, Michael Clark, Chris Dickens, Natalia Estrada Carmona, Alexander K. Fremier, Sarah K. Jones, Colin K. Khoury, Rattan Lal, Michael Obersteiner, Roseline Remans, Adrien Rusch, Lisa A. Schulte, Jeremy Simmonds, Lindsay C. Stringer, Christopher Weber and Leigh Winowiecki
https://sc-fss2021.org/wp-content/uploads/2021/07/FSS_Brief_Nature_Positive_Agriculture.pdf

Delivering climate change outcomes with agroecology in low- and middle-income countries: evidence and actions needed
by Sieglinde Snapp, Yodit Kebede, Eva Wollenberg, Kyle M. Dittmer, Sarah Brickman, Cecelia Egler, Sadie Shelton
(May, 17, 2021)
doi.org/10.48565/scfss2021-2420

C. Actions for Equity, Inclusiveness and Nutrition and Health

A review of evidence on gender equality, women's empowerment, and food systems
by Jemimah Njuki, Sarah Eissler, Hazel Malapit, Ruth Meinzen-Dick, Elizabeth Bryan, and Agnes Quisumbing (May 11, 2021)
doi.org/10.48565/scfss2021-1q69

Marginal areas and indigenous people – Priorities for research and action
by Sayed Azam-Ali, Hayatullah Ahmadzai, Dhrupad Choudhury, Ee Von Goh, Ebrahim Jahanshiri, Tafadzwanashe Mabhaudhi, Alessandro Meschinelli, Albert Thembinkosi Modi, Nhamo Nhamo, Abidemi Olutayo (April 5, 2021)
doi.org/10.48565/fd4f-rk35

The White/Wiphala Paper on Indigenous Peoples' food systems
by Members of Global-Hub and of the technical editorial committee. Danny Hunter (Alliance of Bioversity International and CIAT); Gam Shimray (Asian Indigenous Peoples Pact); Thomas Worsdell; (Asian Indigenous Peoples Pact); Anne Brunel (FAO Indigenous Peoples Unit); Gennifer Meldrum (FAO Indigenous Peoples Unit); Ida Strømsø (FAO Indigenous Peoples Unit); Luisa Castañeda (FAO Indigenous Peoples Unit); Mariana Estrada (FAO Indigenous Peoples Unit); Mikaila Way (FAO Indigenous Peoples Unit); Yon Fernandez de Larrinoa (FAO Indigenous Peoples Unit); Charlotte Milbank (FAO Indigenous Peoples Unit, University of Cambridge); Tania Martinez (Greenwich University, Natural Resources Institute); Harriet Kuhnlein (McGill University, Centre for Indigenous Peoples' Nutrition and Environment); Bhaskar Vira (University of Cambridge)
doi.org/10.4060/cb4932en

Priorities for inclusive urban food system transformations in the Global South
by Paule Moustier, Michelle Holdsworth, Dao The Anh, Pape Abdoulaye Seck, Henk Renting, Patrick Caron, Nicolas Bricas (May 10, 2021)
doi.org/10.48565/3xdb-qq20

Secondary Cities as Catalysts for Nutritious Diets in Low- And Middle-Income Countries
by Kesso Gabrielle van Zutphen, Dominique Barjolle, Sophie van den Berg, Breda Gavin-Smith, Klaus Kraemer, Capucine Musard, Helen Prytherch, Johan Six, Simon Winter, Kris Woltering (April 2021)
https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Secondary_Cities.pdf

The Future of Small Farms: Innovations for Inclusive Transformation
by Xinshen Diao, Thomas Reardon, Adam Kennedy, Ruth S. DeFries, Jawoo Koo, Bart Minten, Hiroyuki Takeshima, and Philip Thornton (April 2021)
https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Small_Farms.pdf

Fruits and vegetables for healthy diets: Priorities for food system research and action
by Jody Harris, Bart de Steenhuijsen Piters, Stepha McMullin, Babar Bajwa, Ilse de Jager, and Inge D. Brouwer (March 2021)
doi.org/10.48565/scfss2021-ys30

Safeguarding and using Fruit and Vegetable Biodiversity
by Maarten van Zonneveld, Gayle M. Volk, M. Ehsan Dulloo, Roeland Kindt, Sean Mayes, Marcela Quintero, Dhrupad Choudhury, Enoch G. Achigan-Dako, Luigi Guarino (April 2021)
doi.org//10.48565/scfss2021-rz27

Addressing Food Crises in Violent Conflicts
by Birgit Kemmerling, Conrad Schetter, Lars Wirkus (April 2021)
doi.org/10.48565/scfss2021-h009

COVID-19 and Food Systems: Rebuilding for Resilience
by Patrick Webb, Derek J. Flynn, Niamh M. Kelly, Sandy M. Thomas, and Tim G. Benton on behalf of the Global Panel on Agriculture and Food Systems for Nutrition (May 2021)
doi.org/10.48565/scfss2021-g940

In the age of pandemics, connecting food systems and health: a Global One Health approach
by Gebbiena M. Bron, J. Joukje Siebenga, Louise O. Fresco (February 15, 2021)
doi.org/10.48565/scfss2021-z850

D. Actions for Sustainable Resource Use and Foresight

Pathways to Advance Agroecology for a Successful Transformation to Sustainable Food Systems
by Urs Niggli, Martijn Sonnevelt, Susanne Kummer (June 2021)
doi.org/10.48565/scfss2021-wf70

Water for Food Systems and Nutrition
by Claudia Ringler, Mure Agbonlahor, Kaleab Baye, Jennie Barron, Mohsin Hafeez, Jan Lundqvist, J.V. Meenakshi, Lyla Mehta, Dawit Mekonnen, Franz Rojas-Ortuste, Aliya Tankibayeva, Stefan Uhlenbrook May 2021) doi.org/10.48565/scfss2021-tg56

Crop Diversity, its Conservation and Use for Better Food Systems. The Crop Trust Perspective
by Stefan Schmitz, Rodrigo Barrios, Hannes Dempewolf, Luigi Guarino, Charlotte Lusti, Janet Muir (April 2021) doi.org/10.48565/scfss2021-j983

Climate Change and Food Systems
by Alisher Mirzabaev, Lennart Olsson, Rachel Bezner Kerr, Prajal Pradhan, Marta Guadalupe Rivera Ferre, Hermann Lotze-Campen (May 2021)
https://sc-fss2021.org/wp-content/uploads/2021/05/FSS_Brief_Climate_Change_and_Food_Systems.pdf

Reduction of Food Loss and Waste – The Challenges and Conclusions for Actions Findings and Recommendations for Actions of an international Conference by the Pontifical Academy of Sciences with the Rockefeller Foundation
by Joachim von Braun, Marcelo Sánchez Sorondo and Roy Steiner (February 15, 2021)
doi.org/10.48565/scfss2021-dw50

Livestock and sustainable food systems: Status, trends, and priority actions
by Mario Herrero, Daniel Mason-D'Croz, Philip K. Thornton, Jessica Fanzo, Jonathan Rushton, Cecile Godde, Alexandra Bellows, Adrian de Groot, Jeda Palmer, Jinfeng Chang, Hannah van Zanten, Barbara Wieland, Fabrice DeClerck, Stella Nordhagen, Margaret Gill (July 2021, draft)
https://sc-fss2021.org/wp-content/uploads/2021/07/FSS_Brief_Livestock_Sustainable_Food_Systems.pdf

The Vital Roles of Blue Foods in the Global Food System
by Jim Leape, Fiorenza Micheli, Michelle Tigchelaar, Edward H. Allison, Xavier Basurto, Abigail Bennett, Simon R. Bush, Ling Cao, Beatrice Crona, Fabrice DeClerck, Jessica Fanzo, Jessica A. Gephart, Stefan Gelcich, Christopher D. Golden, Christina C. Hicks, Avinash Kishore, J. Zachary Koehn, David C. Little, Rosamond L. Naylor, Elizabeth R. Selig, Rebecca E. Short, U. Rashid Sumaila, Shakuntala H. Thilsted, Max Troell, Colette C.C. Wabnitz (April 15, 2021)
doi.org/10.48565/scfss2021-bg71

E. Investment, Finance, Trade and Governance actions

Ending Hunger by 2030 – policy actions and costs
by Joachim von Braun, Bezawit Beyene Chichaibelu, Maximo Torero Cullen, David Laborde, Carin Smaller (March 4, 2021; reprint from Oct.13, 2020)
doi.org/10.48565/scfss2021-kz31

Financing SGD2 and Ending Hunger
by Eugenio Díaz-Bonilla (May 11, 2021)
doi.org/10.48565/scfss2021-ba75

Trade and Sustainable Food Systems
by Andrea Zimmermann and George Rapsomanikis (June 8, 2021)
doi.org/10.48565/scfss2021-zq03

F. Actions in Regions and Countries

Policy options for food systems transformation in Africa – from the perspective of African universities and think tanks
by Fadi Abdelradi, Assefa Admassie, John Asafu Adjaye, Miltone Ayieko, Ousmane Badiane, Katrin Glatzel, Sheryl Hendriks, Mame Samba Mbaye, Fatima Ezzahra Mengoub, Racha Ramadan, Tolulope Olofinbiyi, Simbarashe Sibanda (April 2021)
doi.org/10.48565/scfss2021-6h10

The Role of Science, Technology, and Innovation for Transforming Food Systems in Africa
by Sheryl L. Hendriks, Endashaw Bekele, Thameur Chaibi, Mohamed Hassan, Douglas W. Miano and John H. Muyonga (April 2021)
doi.org/10.48565/scfss2021-a948

The Role of Science, Technology and Innovation for Transforming Food Systems in Latin America and the Caribbean
by Elizabeth Hodson de Jaramillo, Eduardo J. Trigo and Rosario Campos (April 2021)
doi.org/10.48565/scfss2021-6w45

The Role of Science, Technology, and Innovation for Transforming Food Systems in Asia
by Paul J Moughan, Daniel A Chamovitz, S Ayyappan, Morakot Tanticharoen, Krishan Lal, Yoo Hang Kim (April 2021)
doi.org/10.48565/scfss2021-tf41

The Role of Science, Technology, and Innovation for Transforming Food Systems in Europe
by Claudia Canales, Robin Fears (April 2021)
doi.org/10.48565/scfss2021-qb52

Transforming Chinese Food Systems for both Human and Planetary Health
by Shenggen Fan, Jikun Huang, Fusuo Zhang, Wenhua Zhao, Hongyuan Song, Fengying Nie, Yu Sheng, Jinxia Wang, Jieying Bi and Wenfeng Cong (April 18, 2021)
doi.org/10.48565/scfss2021-vq06

Key Areas of the Agricultural Science – Development in Russia in the Context of Global Trends and Challenges
by a Group of Russian Scientific Experts under the Supervision of the Institute of Agricultural Research of the Higher School of Economics (April 2021)
doi.org/10.48565/scfss2021-6265

Food System in India. Challenges, Performance and Promise
by Ashok Gulati, Raj Paroda, Sanjiv Puri, D. Narain, Anil Ghanwat (March 30, 2021)
doi.org/10.48565/scfss2021-b823

ANNEX 2: SCIENCE DAYS

1. STATEMENT ON SCIENCE DAYS

IMPLICATIONS FOR A SCIENCE AGENDA FOR THE UNITED NATIONS FOOD SYSTEMS SUMMIT 08-09 JULY 2021

A report prepared by Rajul Pandya-Lorch, Heike Baumüller, Sundus Saleemi, Preetmoninder Lidder[1]

INTRODUCTION

Science, technology and innovation are essential to accelerate the transformation to healthier diets and more sustainable, equitable and resilient food systems. What science and innovation are needed and how they can inform related policies were the focus of the Science Days, a virtual conference organized by the Scientific Group to the UN Food Systems Summit and facilitated and hosted by the Food and Agriculture Organization of the United Nations on July 8-9, 2021 (see Annex 1 for the program). In addition, partners held more than 40 side events on July 5-7 to present their insights on science, technologies and innovations that can drive food systems transformation (see Annex 2).

More than 2,000 participants from research, policy, civil society and industry came together to examine how to unlock the full potential of science, technology, and innovation to transform food systems. They also discussed:

- advancing science-based options for achieving more healthy diets and more inclusive, sustainable and resilient food systems;
- putting science to work, especially through stronger science-policy interfaces, investments in institutional and human capacity, and capitalizing on models and data;
- addressing missed opportunities and contentious issues hindering the advancement of science;
- empowering and engaging key players, including youth, Indigenous Peoples, food industry and start-ups, and women;
- pushing the frontiers of science, especially in bio-science innovations, digital innovations, and policy and institutional innovations; and
- looking ahead to the world in 2030 and beyond, and prioritizing urgent actions to achieve Agenda 2030 and the Sustainable Development Goals (SDGs), especially SDG2.

Brief highlights of the discussions that took place during the two days follow, with an emphasis on opportunities for investments in science and knowledge and evidence gaps that must be addressed to meaningfully and successfully transform food systems to achieve ending hunger and ensure more healthy diets, as well as enabling more inclusive, sustainable and resilient food systems.

1. SCIENCE FOR THE FOOD SYSTEMS SUMMIT: UNLOCKING THE POTENTIAL OF SCIENCE, TECHNOLOGY AND INNOVATION (STI) FOR FOOD SYSTEMS TRANSFORMATION

QU Dongyu, Director-General, United Nations Food and Agriculture Organization (FAO), highlighted the need to adopt *"a holistic, coordinated approach to transform our agri-food systems"* and stressed that *"to achieve the ambitious transformative changes required, we need to change policies, mindsets, behaviours and business models."*

Amina Mohamed, UN Deputy Secretary-General and Moderator of the Summit Advisory Committee, emphasized that *"food systems transformation demands that we deepen our understanding of how to best calibrate our policies and investments, so they address all dimensions of sustainable development…. It's no longer enough to think only of enhancing productivity. We must also account for the relationship with human and planetary health."*

Agnes Kalibata, UN SG's Special Envoy for the 2021 Food Systems Summit*,* underlined that food systems

1 Rajul Pandya-Lorch is a senior communications adviser in food policy; Heike Baumüller is Coordinator, Program for Accompanying Research for Agricultural Innovation (PARI) and Senior Researcher, Center for Development Research (ZEF), University of Bonn; Sundus Saleemi is Senior Researcher, Pakistan Institute of Development Economics and Center for Development Research (ZEF), University of Bonn; and Preetmoninder Lidder is Technical Adviser, Food and Agriculture Organization of the United Nations (FAO).

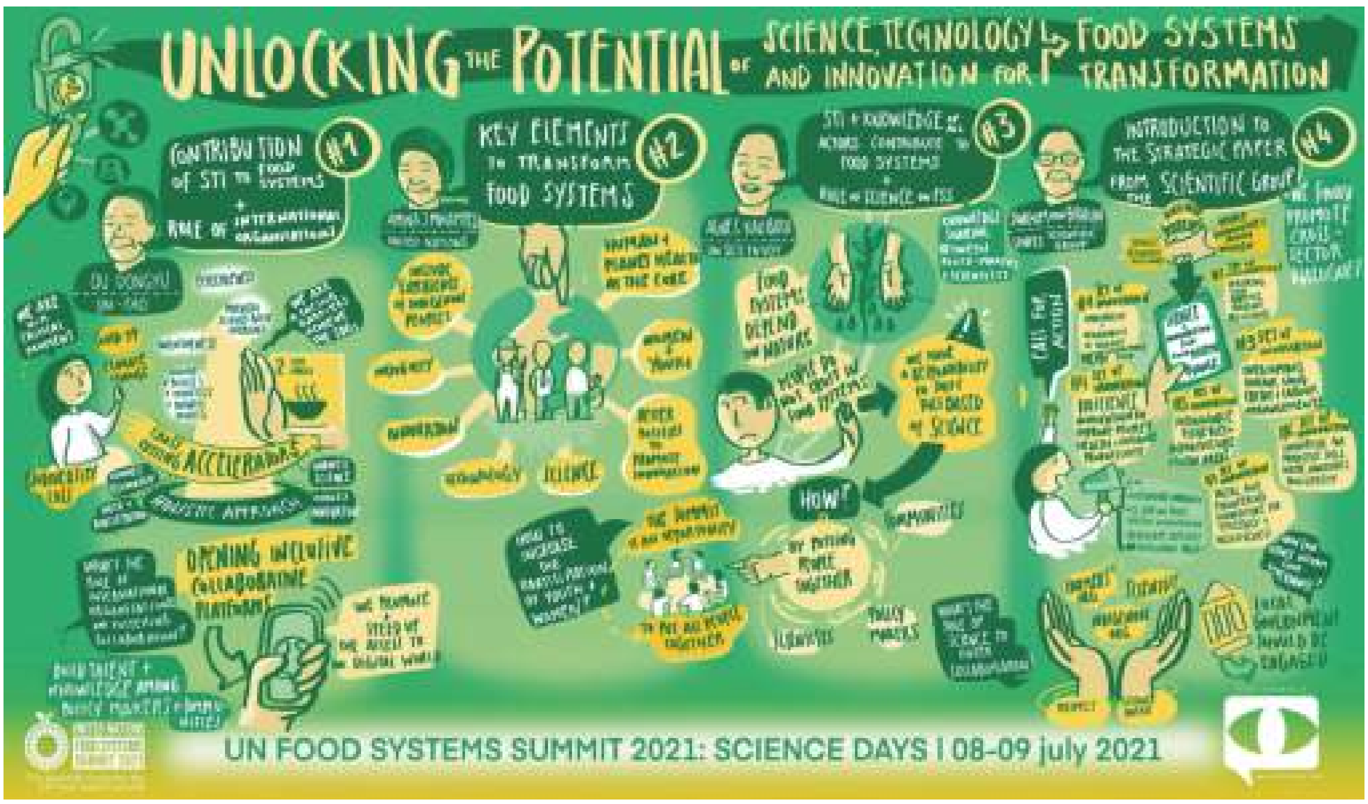
transformation will contribute towards achieving multiple SDGs, noting that *"the complexity and importance of agri-food systems need to be recognized, not only to combat hunger and malnutrition, but also to reduce inequalities and eradicate poverty."*

Joachim von Braun, Chair of the Scientific Group, stressed the need for an interdisciplinary approach to food systems transformation, urging that *"all sciences – natural sciences and social sciences, basic sciences and applied sciences – can and must deliver the innovations needed for food systems transformation."* He presented a set of seven science-driven innovations[2] put forward by members of the Scientific Group to catalyze, support and accelerate food systems transformation to achieve the Summit goals:

1. Innovations to end hunger and increase the availability and affordability of healthy diets and nutritious foods.
2. Innovations to de-risk food systems and strengthen resilience, in particular for negative emission farming and climate-resilient food systems.
3. Innovations to overcome inefficient and unfair land, credit, and labor arrangements, and to facilitate the inclusion, empowerment and rights of women and youth.
4. Bio-science and digital innovations for improving people's health, enhancing systems' productivity, and restoring ecological well-being.
5. Innovations to keep – and, where needed, regenerate -- productive soils, water and landscapes, and protect the agricultural genetic base and biodiversity.
6. Innovations for sustainable fisheries, aquaculture, and the protection of coastal areas and oceans.
7. Engineering and digital innovations for the efficiency and inclusiveness of food systems and the empowerment of rural communities.

Governance and the role of science in food systems governance was a key theme that emerged during the discussions, with speakers (i) calling on governments to invest in STI, noting that current levels are insufficient; (ii) calling for intergovernmental action, noting that food systems science cannot be undertaken by a single ministry; and (iii) calling for local governments to be engaged as food systems are local, ecology is local, and natural resources are local.

SCIENCE FOR THE FOOD SYSTEMS SUMMIT: UNLOCKING THE POTENTIAL OF SCIENCE, TECHNOLOGY AND INNOVATION (STI) FOR TRANSFORMATION OF FOOD SYSTEMS



2 These are presented in greater detail in the strategic paper on **Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit** by Joachim von Braun, Kaosar Afsana, Louise O. Fresco and Mohamed Hassan, July 2021.

Another key theme focused on collaboration between scientists and other stakeholders, with speakers urging scientists to engage with citizens and be prepared to answer difficult questions, calling on scientists not to "talk about" but rather "talk with" Indigenous Peoples and other communities, and suggesting that platforms should be created or strengthened to facilitate collaboration between scientists and other knowledge communities in food systems.

2. SCIENCE AS ACTION: SCIENCE-BASED OPTIONS TO ACHIEVE MORE HEALTHY DIETS AND MORE INCLUSIVE, SUSTAINABLE, AND RESILIENT FOOD SYSTEMS

2A. Achieving more healthy diets in food systems – STI for affordable and accessible nutritious foods for healthy diets

This session focused on science, technology, policy and institutional innovations to enhance productivity, and incentivize the availability, affordability, and uptake of nutritious and safe foods.

Several knowledge/evidence gaps were highlighted, including the notion that more research/evidence is needed on (i) the effects – including environmental effects – of different types of diets including plant-based diets (vegan/vegetarian) and aquatic foods; (ii) the effects of different policy interventions on consumption patterns; and (iii) approaches for reducing anti-microbial resistance. Concepts and definitions should be standardized based on a unified approach towards health. Large, standardized data sets – especially in/for Africa – should be collected. Collaboration among researchers, innovators, and regulatory bodies needs to be enhanced.

The role of bioinformatics and nanotechnologies in ensuring food safety standards needs to be better understood. Modalities need to be explored for strengthening local food chains for improving the access to and affordability of diversified diets, and minimizing food loss and waste. The issue of healthy diets should be approached holistically, i.e. using the One Health approach, i.e. the notion that human, animal, plant and planetary health are interconnected and interdependent.

2B. Achieving more inclusive food systems – STI for eliminating hunger and poverty and advancing equitable livelihoods

This session focused on science, technology, policy and institutional innovations to eliminate hunger, malnutrition and poverty and advance equitable livelihoods.

Technological and institutional innovations in food systems have enabled great progress in hunger reduction and improvement, but with massive adverse consequences for planetary health and social justice. Despite the advances in the production of staple food crops that help to increase global caloric availability, food systems fail to provide healthy diets for all with additional challenges caused by the COVID-19 pandemic. Huge social disparities across and within countries persist, notably – for example – between rural and urban areas, which have led to inequities in access to resources and institutional participation. Thus, innovations need to be more inclusive and should not exclude some food systems actors.

Several key knowledge and evidence gaps emerged during the discussion, such as which technology bundles are required to boost productivity of smallholders, how to change institutional frameworks/bring forward institutional change to make food systems more inclusive and reduce social inequities, and how to avoid overlooking negative externalities of proposed solutions (e.g. small-scale irrigation and consequences on water availability).

2C. Achieving more sustainable and resilient food systems – STI for making sustainable use of natural resources and managing and preventing risks and crises, including climate change and COVID-19

This session focused on science, technology, policy and institutional innovations to achieve more sustainable and resilient terrestrial and marine-based food systems and foster more climate-neutral, climate-positive, and climate-resilient food systems.

Diversification can play an important role in increasing the resilience of food systems at various levels. In food production, for instance, resilience could be built through the diversification of cultivars or by shifting from annual to perennial cropping systems. Diversification efforts should focus on both the protection of the existing agro-biodiversity and farming systems as well as the development of new approaches, such as breeding of new cultivar(s) that are better adapted to changing conditions. Diversification of food baskets – including a greater focus on indigenous foods – could increase resilience at the consumption level. A more holistic view of food production is also needed that goes beyond a focus on staple crops to take into account crop production, animal husbandry, forestry and non-food uses of biological resources.

Building resilience will require structural changes, not only at the individual level but also at the societal and cultural level. Farmers are risk averse, but not necessarily technology averse. To mainstream STI, there is a need to understand farmers and establish trust between farmers and scientists. Another way to facilitate the adoption of STI and reduce risks is by working with communities, enabling participants to decide which technologies to adopt.

3. PUTTING SCIENCE TO WORK: SCIENCE, PEOPLE AND POLICY

3A. Strengthening the science-policy interface across disciplines and policy areas including economics, and health-, nutrition-, climate-, ecological-sciences

This session focused on how to strengthen the science-policy interface at the national and international levels to enable food systems transformation.

Three key features are necessary for a successful science-policy interface: (i) salience, translating science and knowledge in ways that are relevant to policy-makers; (ii) credibility, holding high scientific quality and being trustworthy; and (iii) legitimacy, being viewed by stakeholders as the appropriate body for the job. The accountability and inclusiveness of such an interface are also important. Research has both an ex ante and ex post role in policy-making. Science informs policies based on existing evidence but must also continuously gather new evidence through the evaluation of policies in place. Science-policy interfaces must play both of these roles. The lags between innovations and the markets and those between end users and innovators can be reduced by strengthening science-policy platforms.

At the national level, platforms that can bring together all of the stakeholders – ministries, researchers, data repositories – from different disciplines are needed. At the international level, there is a need for an intergovernmental mechanism: speakers called for more investigation on whether we should build on what currently exists or create a new body.

Discussions also highlighted the notion that unsustainable food system subsidies must be replaced with policy innovations. Scientists can help policy-makers to design policies that help to achieve multiple goals/wins. Such policies can be designed by identifying synergies, and multidisciplinary and collaborative research is a pre-requisite for identifying these synergies.

3B. Investing in institutional and human capacity for science and innovation

This session focused on the type of investments needed to strengthen institutional and human capacity to enable food systems transformation.

Regional and international collaborations in food system science need to be promoted and funds provided to support programs that empower youth, farmers, and women. The role of academics and science in building institutions can be strengthened through global networks that generate new types of knowledge and enable collaboration at the local, national, and global levels by bringing together different expertise. New programs, projects, and ways of teaching to overcome old barriers are required. Curricula and training courses need to be updated and state-of-the-art materials included. Greater emphasis needs to be placed on transdisciplinary research and education (in terms of courses and degrees). In addition, to make related studies more attractive to students, mindsets need to be changed to see food system activities as a business, whereby entrepreneurs in agribusiness and R&D can act as role models and support innovations from idea to output and give practical examples. A more efficient food system demands not only adjustments on the production side, but also a shift in the mindset of consumers to foster healthy diets. Changing consumption patterns towards more sustainable and healthy diets requires investments in human resources (e.g. nutritionists, food advisers) and educating the younger generation.

As future food systems become increasingly knowledge-intensive, universities (and research organizations) require increased financial support to play a key role in food systems transformation. This could be achieved through specific official development assistance (ODA) designed to support science and technology in the recipient country by making science an integral part of development projects (with a percentage of ODA-funded programs and projects going to local and national research organizations, such as academies and universities) aimed at strengthening research and higher educational systems.

3C. Capitalizing on models, data, and communications revolutions, and new methods

This session focused on capitalizing on and expanding investments in models, data, methods, and communications to enable food systems transformation.

Speakers highlighted the utility of models as labs where innovations can be tested to understand their direct and indirect effects. This is particularly useful regarding food systems that are highly complex. Different types of models and other data-driven tools can be applied in this regard. For instance, crop models can assess the impacts of innovations on agricultural productivity or landscapes. They can also predict yields in specific contexts to inform crop insurance schemes. Initially developed at the field scale, they are increasingly also being applied at regional and global scales. However, they have limitations, as it is only possible to model a certain range of crops, and information on different management approaches is limited. Another important source of data is satellite images, which can be used – for example – for damage assessments and early warning. However, the local context can constrain their use: analysis of smallholder landscapes is difficult due to mixed crops and landcover, often making additional fieldwork necessary.

To take full advantage of these analytical tools in the study of food systems, it will be important to integrate different types of models, including crop models, economic models or GIS-based tools. This remains a major challenge. Limited data availability can also reduce the extent to which these tools can be applied. Moreover, data alone will not be enough; rather, the tools need to be based on sound theory and decision support systems to make sense of the data. In addition, further efforts are urgently needed to bridge the last mile to end users and provide them with the necessary information to assist them with decision-making on the ground.

4. WHY THE FIGHT: GETTING TO GRIPS WITH MISSED OPPORTUNITIES AND CONTENTIOUS ISSUES IN SCIENCE AND INNOVATION FOR FOOD SYSTEMS

This session explored the causes of important lingering and emerging food systems-related science controversies, as well as missed opportunities in STI for food systems transformation, and discussed the role of research to address such controversies and move beyond polarization. Speakers highlighted several missed opportunities and contentious issues concerning (i) agro-ecology, (ii) protein from aquatic foods, and (iii) biotechnology.

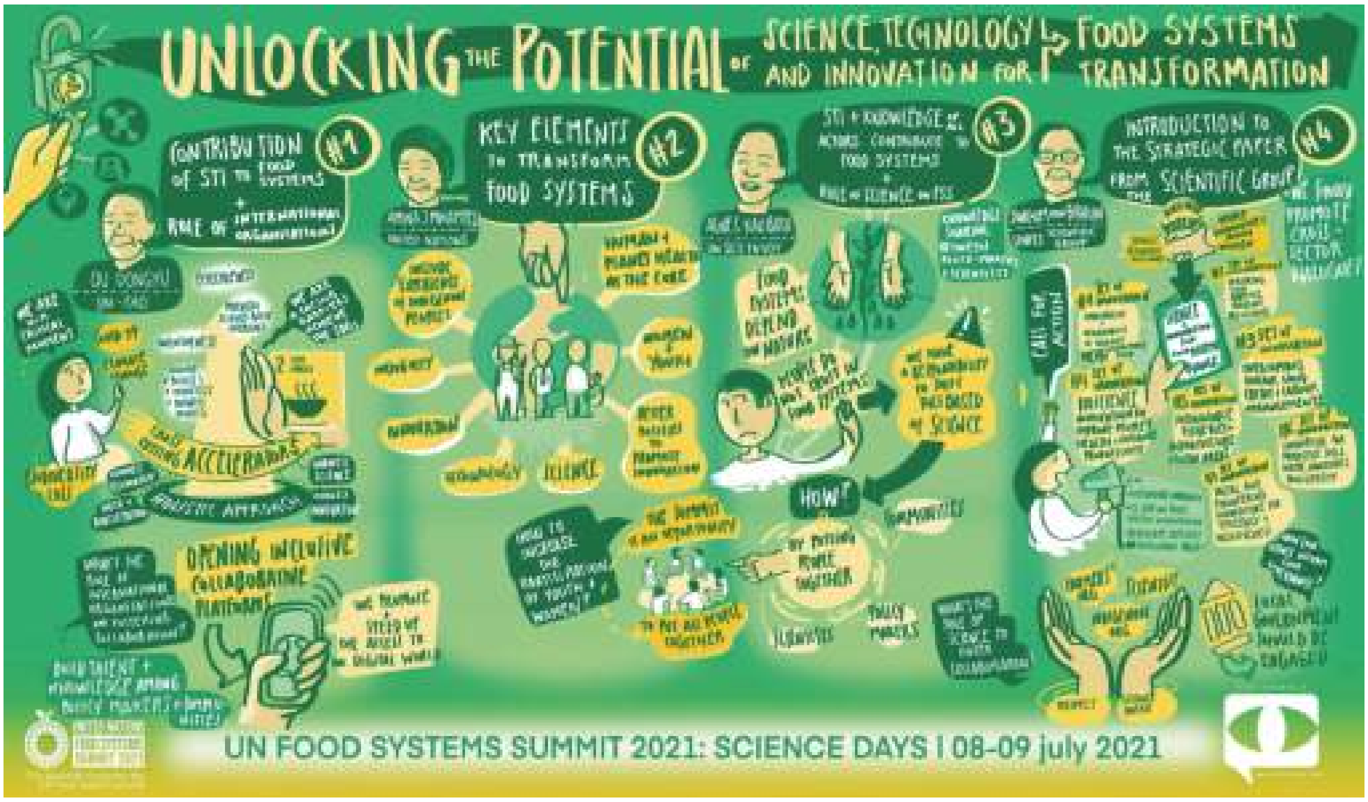
Agroecology is about diversification (diversification of landscapes, actors, knowledge [traditional/scientific]), which reduces trade-offs between ecosystems and natural resources and food productivity. To mainstream agroecological practices, it is important to address incoherent policies, excessive dependency on markets, and inadequate participation of citizens. Any diversification strategy needs to be context specific. Diversification is not a contradiction to productivity, nor is it the sole solution to the problem, but it can enhance the resilience of food systems.

Protein from aquatic foods is a missed opportunity to transform food systems. Diversification should include diverse foods from land and water systems. A major challenge is to change the narrative from feeding to nourishing, which gives an entry point to transform water systems (e.g. in Cambodia, the most important part of the diet is aquatic food). More research is needed on the implications of incorporating wild aquatic foods, e.g. seaweed that are high in micronutrients and protein, into diets. The importance of wild food in general appears to be underestimated, and more data and research are needed on this.

Biotechnology alone cannot solve the issue of hunger, but it is a part of the solution. CRISPR provides the ability to increase the quantity and quality of yields, as well as the micronutrient content of those yields. However, the political economy strongly influences the functioning of food systems. Science can be the solution if there are the right incentives in place. The major issue is having the right incentives in policy. Technology needs to be regulated based on its outcomes.

A challenge is also posed by misinformation about what would be required to create sustainable food systems, and at the same time provide financial returns for all stakeholders. Scientists can help in amplifying the voice for new tools that can drive the necessary policies and support the critical dialogues engaging policy-makers. Scientists producing evidence can put it in context, advise, and suggest pathways to implementation.

WHY THE FIGHT: GETTING TO GRIPS WITH MISSED OPPORTUNITIES AND CONTENTIOUS ISSUES IN SCIENCE AND INNOVATION FOR FOOD SYSTEMS



5. ACHIEVING THE 2030 GOALS: OPPORTUNITIES, TRADE-OFFS, OBSTACLES AND SYNERGIES

Drawing upon global foresight models and scenario exercises, this session looked ahead to the world in 2030.

Food systems are threatening key planetary boundaries, with some critical boundaries already being surpassed. Feeding the world is currently at odds with sustainable food production. Tackling the food system challenges demands a systemic approach and the provision of cross-cutting knowledge. Therefore, research and public policies need to be connected and actions from all actors in the area must be mobilized. Food system transformation needs to address both the supply and demand side in a holistic way starting from research output that addresses societal needs to policy-making that integrates the civil society. Participatory governance and research are key. Investment in multi-stakeholder partnerships is mandatory, and communities must be empowered to become part of research and policy processes. Asymmetries in information need to be reduced (e.g. through trade and knowledge). It is crucial to involve citizens in making science choices, rather than just explaining to them technologies based on risk assessment.

For Africa, as the majority of its population lives in rural areas and engages in agriculture, a vibrant agricultural sector is required to achieve inclusive development and socioeconomic transformation. This requires financial and infrastructure capacity building and investment in human capital. African investment in national public research is critical but insufficient. Trade and regulation are key for food systems transformation. Intra-African trade needs to be boosted, and free access to global food markets is critical.

ACHIEVING THE 2030 GOALS: OPPORTUNITIES, TRADE-OFFS, OBSTACLES AND SYNERGIES

6. EMPOWERING AND ENGAGING KEY PLAYERS IN FOOD SYSTEM INNOVATION

6A. Youth

This session focused on how to effectively and appropriately engage, include, incentivize, and empower youth in science and innovation for food systems transformations.

Today's youth are the decision-makers of tomorrow. It is crucial to engage youth on two fronts: on the one hand, there is a need to capitalize on their potential, knowledge and ideas to foster innovation for food system transformation, and on the other hand there is a need to listen to them and their needs on an equitable basis.

Food systems transformation must be inclusive of the youth. Meaningful representation is the key to meaningful engagement. Youth are still under-represented, especially in international fora. This is a manifestation of power imbalances and lack of inclusiveness (and lack of understanding of thereof). Science is essential not only in providing innovative ideas and knowledge for food systems transformation, but also as a platform of engagement of youth at local and global scales through interdisciplinary, intergenerational and intercultural networks. At the same time, acting only at the international level is not sufficient because many groups are not represented at this level. Youth must be approached at both national and grassroots levels where young people self-organize in informal ways on a voluntary basis, but without proper resources for action.

Youth have a particularly high stake in ensuring climate justice, which needs to go hand in hand with environmental and food justice. Trade-offs between these goals may exist and need to be addressed. This requires collective multilateral approaches. Youth can be drivers of change in this regard rather than passive beneficiaries.

6B. Traditional and indigenous knowledge

This session focused on how to effectively and appropriately support and use traditional and Indigenous Peoples' knowledge and facilitate access and benefit-sharing.

Speakers highlighted that indigenous food systems are multifunctional and holistic, as well as self-sufficient and nutritious. Nature not only generates food but medicine, shelter, energy and supports cultural identity, social and spiritual life. Additionally, Indigenous Peoples' innovations do not deplete natural resources or increase carbon emissions. Women are knowledge keepers, sharing and sustaining knowledge by passing it on to their descendants. However, it is insufficient to only acknowledge this, but rather the move must take place from acknowledgment to specific actions. It is necessary to let the keepers of knowledge sit at decision tables, not only to protect their knowledge but also to confer the lessons of their knowledge about resilience and sustainability to address global challenges. Furthermore, it is important to recognize Indigenous Peoples' knowledge and treat it equally with other knowledge systems, continue to encourage transdisciplinary collaborative research and co-production of knowledge that will support equitable benefit-sharing, and promote collaboration and network of champions for up-scaling. To empower and engage knowledge holders, universities and scientific bodies should participate in local initiatives and integrate indigenous knowledge into school curricula.

Going forward, the key knowledge gap to address is how to better integrate Indigenous Peoples in decision-making and scientific processes.

6C. Science in and by the food industry and start-ups

This session focused on how to effectively and appropriately support and use science in and by the food industry and start-ups, and foster partnerships between food industry science and public sector, academia and civil society science.

This session showcased private sector-led examples of technological and institutional innovations that can support the achievement of the SDGs on several levels. In India, for instance, innovations have benefited smallholders (satellite imagery/ remote sensing), contributed to reducing poverty (white revolution) and improved nutrition (biofortification). Cultured meat as an alternative protein source can support food security by providing nutritious and affordable food cost-effectively and with a smaller environmental footprint. Innovations in the blue sector (including capture fisheries, aquaculture and non-fish aquatic foods) can improve the access to and affordability of healthy and diverse diets. Cultured meat and aquatic foods, along with other innovations, could strongly increase not only the quantity but also the quality of protein, whereby the latter is often overlooked especially in low- and middle-income countries.

Developing and commercializing technological and institutional innovations requires a supportive start-up ecosystem that engages local communities and industry. In particular, challenges related to product registration and regulations for new products and novel foods remain to be addressed in many lower-income markets. A lack of harmonization currently inhibits advancement, given that all countries have different regulatory processes. The EU could be a useful role model in this regard. Innovation environments should support both incremental and transformative innovations to improve food systems and achieve sustainable agriculture.

Sustainability in the aquatic foods sector will be key to its long-term viability. Both the private and public sectors have to be involved for sustainable fisheries and aquaculture. Good resource management systems for public goods (i.e. fisheries) need to operate across borders and should be based on science. On the other hand, the industry has a responsibility to harvest with the right tools, reduce pressure on fisheries by sustainably increasing fish farming around the world, and share knowledge on breeding for improvements of growth and a reduction of disease outbreaks.

6D. Women

This session focused on strengthening rights, and the effective and appropriate engagement, inclusion, and empowerment of women in science and innovation for food systems transformation.

Speakers highlighted that there exist synergies between the two goals of achieving more gender equal societies and economies and the transformation of food systems into more equitable and sustainable food systems. Processes that disempower women are also those that exclude women from food systems. However, food systems and gender relations are diverse, and this diversity should be considered when prioritizing the pathways towards food systems transformation. Land and credit are the key resources that can empower women, although women have reduced access to these two key resources. Women's access to markets is hindered by cultural norms, gender-based violence, and limited mobility exacerbated by unavailability of affordable transport. Greater access to markets has been evidenced to improve women's decision-making as well as improved incomes and nutritional outcomes. The pathways to gender equity and food system transformation are similar. Both require not only science-driven innovations but also social, legal, and cultural change.

The key knowledge and evidence gaps needed to address the overarching question of how to induce food system transformation to gender equitable food systems include:

- How to limit hijacking of social networks among women by privileged individuals (and men).
- How to identify and create new business models that put women at the center.
- How to engage men in the empowerment process, and create male champions for gender equality.
- How to understand intra-household inequalities to induce change towards gender equitable food systems, particularly at scale.
- How to break the default male-oriented system (not only the food system).

7. BRAVE NEW WORLD: PUSHING THE FRONTIERS OF SCIENCE FOR FOOD SYSTEMS

7A. Bio-science innovations

This session focused on the frontiers of science for food systems, in this case the frontiers of bio-science innovations such as genome editing, synthetic biology, microbiomes, alternative protein sources, alternative sources for essential micronutrients, cell factories and more.

Bio-sciences offer various opportunities to tackle malnutrition. For instance, this includes the use of underutilized crops to increase the diversity of the gene pool, technologies for precision selection and accelerated crop improvement, and biofortification to improve nutritional quality of foods that are easily accessible for a large population. Bio-sciences also have strong potential to impact personalized nutrition (i.e. nutrition that takes into consideration individual genetics, phenotype, dietary habits, etc.), but research in this area is still at an early stage.

Related innovations can also contribute to more sustainable production. Although synthetic fertilizers/pesticides have allowed us to significantly increase agricultural production and reduce food insecurity, their mis-use can have serious adverse effects for biodiversity and human health. There are many promising bio-based innovations that can help make agricultural production more sustainable (e.g. artificially synthesized pheromones to control insect populations, microbiome-based inputs to improve carbon sequestration, reduce methane emissions from ruminants, etc.). Synthetic biology will also have an important role in vaccine development (e.g. for cattle). In the long run, these technologies could be personalized for different micro-environments (personalized farming). As bio-science innovations are developed, it is important to understand the needs of those who will use these new technologies at all stages of the value chain. For example, what do farmers want from bio-inputs? What do end consumers want from alternative protein sources?

Moreover, developing technologies is insufficient; rather, these technologies must be available to smallholders, and smallholders must have the resources needed to adopt them if they wish to do so. Regional harmonization on standards can speed up the adoption and increase transparency of suitable biotechnologies. More coherent regulatory frameworks can avoid creating barriers for competition, trade, and innovation. In some cases, regulating products instead of technologies may be preferable (e.g. not restricting the use of gene-editing, but creating regulations to ensure that the technology will not be mis-used).

7B. Digital innovations

This session focused on the frontiers of science for food systems, in this case the frontiers of digital innovations such as artificial intelligence, machine learning, the Internet of Things, remote sensing, big data analysis, robotics, and more.

Many digital tools are now available in the different agricultural sub-sectors, in particular crop and livestock production, which support farmers with information, access to markets and financial services. Additional investments are needed to move more of these solutions to scale and make them available for producers and other food system actors. A better science base will be crucial to inform the design and scaling of these digital tools, requiring closer collaboration between researchers and entrepreneurs. This will allow STI products from the lab/university, etc. to be useful in the farm/market. Building subject matter-expertise among the providers of digital solutions as part of teaching curricula could contribute to bridging this gap. Moreover, better integration of the diverse digital solutions into broader platforms can reduce marketing costs and generate added value for users.

Data protection remains an under-regulated and under-researched issue. A balance must be struck between capitalizing on the data available through the digital tools to inform decision-making and protecting the privacy of data among those that provide it. Users should be given the option to retain their data or be compensated for their use, either financially or through improved service provision. In addition, efforts need to be made to make available data actionable and lead to relevant solutions on the ground. If data access and decision intelligence remain unequal, digital solutions will not level the playing field nor address competitive disadvantages.

7C. Policy and institutional innovations

This session focused on the frontiers of research on policy and institutional innovations such as financing the actions for food systems transformations, repurposing subsidies, innovating taxes, designing regulations, facilitating collective action, governing common goods, revising gender norms, improving market functioning, re-assessing the price and value of food and more.

Economic policy reforms that can help to achieve different goals at the same time need to be developed and implemented. Some of the current subsidies within the food systems, e.g. for intensive animal farms that contribute to environmental degradation, must be redirected to encourage and support sustainable practices. Consideration should be given to promoting technologies such as cellular meat and fish, low impact vertical farming, and regenerative ocean farming as well as public sponsoring of food industry initiatives that promote healthy food habits.

There is a need for eliminating price and market distortions. Market distorting subsidies should be replaced by income supporting programs for low-income consumers and producers. Internalizing the true cost of food into the price of food through taxes or policy instruments should be explored, but it must be considered whether poor people can afford those prices. Social protection would need to be enhanced. True cost accounting must be integrated into national accounting, from GDP account to GEP (growth and ecosystems) accounting. Price surveys, production surveys, and ecosystem services accounting surveys should be integrated.

Continuity of effective policies can be ensured through institutionalizing science-policy interfaces at national and regional levels. Bridging scientific and indigenous knowledge, building consensus on key definitions and communication between policy, science and consumers are some of the key roles for these science-policy interfaces.

There is room for better communication of scientific evidence for effective policies, whereby the trade-offs and synergies of different policies must be clearly articulated and priorities must be identified for policy-makers.

8. LOOKING AHEAD: STRATEGIC FOOD SYSTEMS SCIENCE BEYOND 2030

This session closed the Science Days with reflections on the long-term (beyond 2030) issues, opportunities, and challenges for STI.

The essential role of science for food systems transformation was highlighted throughout this session. While many of the food systems of operated within and by the private sector, governments have a key role to play in creating appropriate macroeconomic frameworks and providing appropriate incentives and regulations to facilitate proper functioning of the private sector, creating positive externalities where the true cost of food is not reflected in market prices, and investing in research and development. Both public and private sectors have important roles to play in research and development. Both basic and applied research are necessary. Investment in scientific research on and for food systems needs to increase by both the public and private sector.

It is insufficient to generate new innovations. Many innovations and solutions already exist that are ready to be implemented. It is critical to understand and overcome hurdles in innovation, including ensuring wider access to innovations, especially by populations that were missed in the millennium agenda.

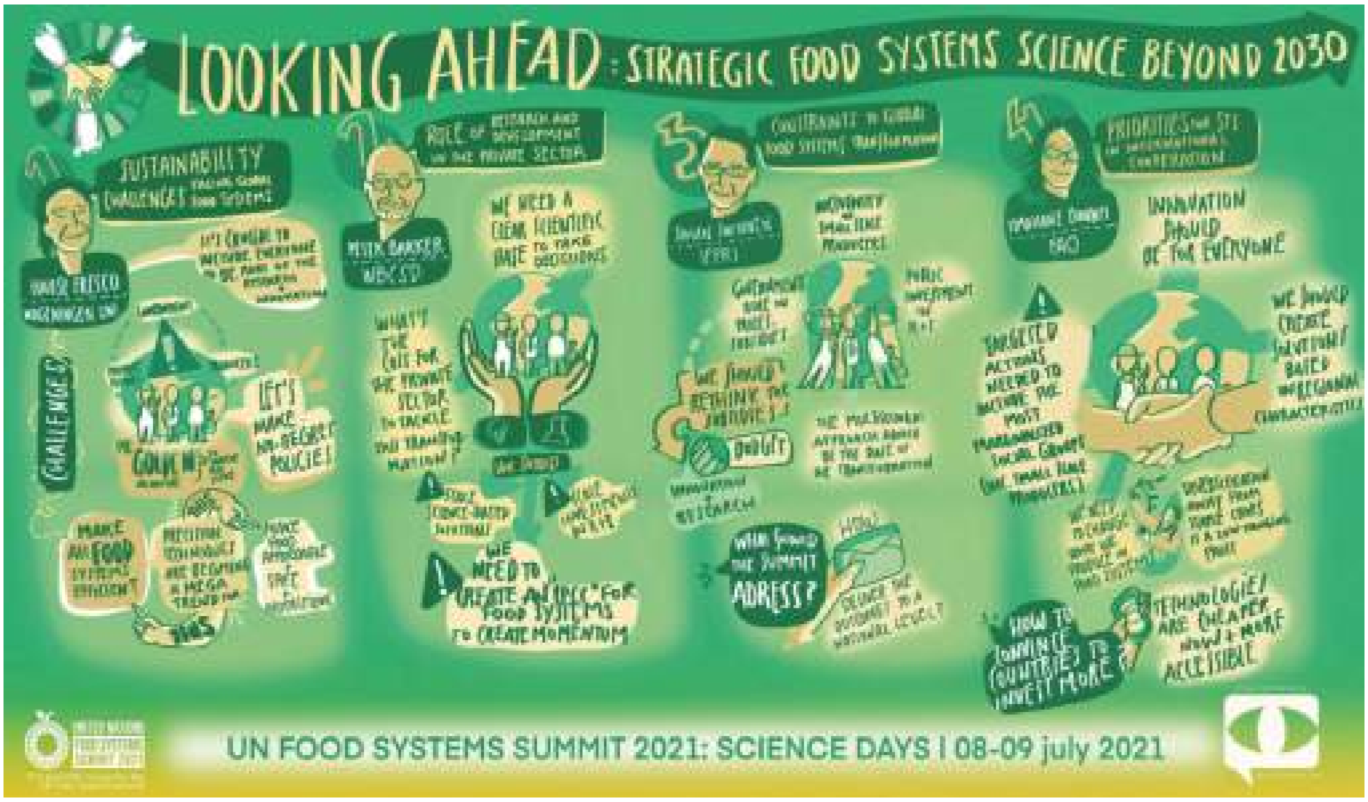
Technology should be adapted to user demands. Farmers and consumers must come together with scientists and be involved in technology design instead of simply being the recipients of technologies. This engagement of science and scientists with the end users will only be effective if it is long term, institutionalized, and iterative.

Food systems transformation and food security is not only about the supply side, but also the demand side. Affordability of healthy diets is a huge issue that must be tackled.

Key areas of research highlighted included assessing the true cost of food, improving resource use efficiency, overcoming hurdles to implementation of innovations, increasing affordability of healthy diets, increasing productivity and production of fruits and vegetables, and reducing food loss and waste.

The need for a global science-policy interface on food systems was highlighted. Suggestions were made for an intergovernmental platform, perhaps along the lines of the IPCC, and more broadly to explore a global agreement for food systems, perhaps along the lines of the Paris Agreement on climate. These would convey and entail a longer-term commitment by governments to overhaul the food systems. A radical change in food systems is needed, not incremental change.

LOOKING AHEAD: STRATEGIC FOOD SYSTEMS SCIENCE BEYOND 2030



CLOSING REMARKS AND WAY FORWARD

Joachim von Braun, Chair of the Scientific Group, reiterated that the Science Days brought together all sciences – social and natural sciences – to facilitate transformation towards sustainable food systems, with the key objective of ending hunger and malnutrition.

While food systems marginalize hunger, this must not be tolerated. The undernourished, youth, women, Indigenous Peoples, and all those who are marginalized have the right of agency on all matters of the food systems. The 1.5 degree global warming goal is equivalent to the zero hunger by 2030 goal. To get there, accelerated science investments and the resulting complex set of innovations need to be one of the top game-changing actions of the Summit.

Science Days was a great learning and research exchange experience. Game-Changing actions partly resulting from the important five Action Tracks that shape Summit agendas were shared. The FSS as a whole needs to become the game changer.

Frontiers of science themes that bring resilience and equity were on the agenda. There was a call for poverty lines to change given that many of them are ridiculously low, not permitting a healthy diet. The opportunities of data revolutions and related analytics were noted, as were the related monopolization risks. Biotechnologies and digitization play a key role in several contexts. Micro-biome research is very relevant for understanding both human nutrition and soil health, plant and animal health, namely One Health. Agroecological approaches should be part of the science agenda, and landscapes need to change, monoculture agriculture abandoned, and digital precision farming innovations embraced to facilitate increased biodiversity. The opportunities for modeling were stressed, and the key role of trade arrangements was highlighted. All sessions touched upon the COVID-19 crisis, and the fragility of the food systems due to climate crises. There were calls for more sharing of science.

Ideas for addressing the finance challenges were shared, and it was noted that both the corporate and public sectors are needed for finance. The InterAcademy Partnership suggested to connect science funding to ODA development program spending. The Scientific Group called upon governments to spend at least the equivalent of 1% of food systems GDP for food systems science.

It was a bold decision by the UN leadership to unleash a multi-stakeholder process as well as invite an independent Scientific Group to mobilize science communities around the world and advise with evidence on the Summit agenda. The science communities broadly welcomed that move by the UN, but it is normal that this is not welcomed by everyone, such as concerns articulated by the HLPE of the CFS. It is time to move to productive so-called "cooperative conflicts", to use a term from Amartya Sen. Proposals are on the table to strengthen existing science-policy interfaces and consider new mechanisms. Academies of sciences and business leaders suggested to establish an IPCC type mechanism for food systems, and it was welcomed that the EU has set up a high-level expert group to sort out such options.

In closing, consideration was given to explore options for continuation of this Science Days format in the future a few times until 2030, including watching progress on the FSS commitments from an independent science perspective.

2. THE AGENDA OF SCIENCE DAYS

The Science Days agenda can be accessed on the website of the Scientific Group (link below). Recordings of all the Science Days sessions and the complete report of the Science Days are also available on the website.

Link: https://sc-fss2021.org/events/sciencedays/program/

3. THE LIST OF SIDE EVENTS OF SCIENCE DAYS

Side Events of the Science Days oragized by global partners of the Scientific Group are listed on the website of the Scientific Group (link below). The highlights of these events are also available on the link.

Link: https://sc-fss2021.org/events/sciencedays/side-events/

ANNEX 3: TERMS OF REFERENCE OF THE SCIENTIFIC GROUP

The terms of reference of the Scientific Group are available at the following link:

https://sc-fss2021.org/wp-content/uploads/2020/11/Terms_of_Reference_web.pdf

About the Scientific Group of the UN Food Systems Summit

The Scientific Group of the UN Food Systems Summit is an independent group of leading researchers and scientists from around the world with a mandate from the United Nations. The Scientific Group is entrusted to deliver independent, state-of-the art, robust, scientific evidence to the UN Food Systems Summit. The Group has published research reports to guide and inform the Summit's policy and investment decisions for the transformation of global food systems. The Scientific Group reports have been appraised and scrutinized by the members of the Group in its series of meetings and have further undergone external peer-review.

The Scientific Group has further brought to the fore diverse perspectives through its network of global partners who have published over forty scientific Briefs in collaboration and dialogue with the Group.

Chair of the Scientific Group is Joachim von Braun, Director of the Center for Development Research (ZEF), Bonn University, and Professor for economic and technological change. Vice Chairs of the Scientific Group are Kaosar Afsana, Kaosar Afsana (Bangladesh) Professor, BRAC James P Grant School of Public Health, BRAC University, Dhaka, Louise O. Fresco (Netherlands) President of the Executive Board, Wageningen University & Research. Mohamed Hassan (Sudan) President of The World Academy of Sciences for the advancement of science in developing countries (TWAS).

Suggested citation:

"von Braun, J., Afsana, K., Fresco, L.O., & Hassan, M. (Ed.). (2021). Science and Innovation for Food Systems Transformation and Summit Actions, Papers by the Scientific Group and its partners in support of the UN Food Systems Summit. ScGroup of the UNFSS (2021), https://sc-fss2021.org"

All publications of the Scientific Group and its partners can be found at www.sc-fss2021.org

@sc_fss2021

Imprint:

Scientific Group of the UN Food Systems Summit 2021
Prof. Joachim von Braun (Chair),
c/o Center for Development Research (ZEF)
Genscherallee 3, 53113 Bonn, Germany
Phone: ++49 (0) 228 / 73 1800
Email: info@sc-fss2021.org

Layout: Druckerei Paffenholz, Bornheim; Yesim Pacal, ZEF