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Gains Foregone by Going GMO Free: Potential Impacts on Consumers, the Environment, and Agricultural Producers

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This paper is dedicated to the memory of Wallace E. Tyner and Wallace E. Huffman; two scholars who made rich contributions to this area of study.

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Introduction

There are more than 820 million people currently undernourished.

GMOs have the capability to increase nutrition security.

Challenges associated with supplying society with food have evolved alongside humanity and the current challenges are more diverse than ever. As both global population and disposable income are expected to increase in the near future (Alexandratos and Bruinsma 2012), more efficient use of natural resources is necessary to deliver dietary needs and wants while limiting the impact of agricultural production on the environment (Tilman et al. 2002). It is important to note that there are more than 820 million people currently undernourished (FAO 2020; WHO 2018), so concerns about providing nutrition security should not be solely focused on needs of future societies. Thus, our current society could benefit from additional innovation and continual innovation will be required to meet the needs of humanity. The ability of genetic improvement techniques, like genetically modified organisms (GMOs), to provide such innovation cannot be trivialized. More than a decade ago, Fedoroff and colleagues (2010) published a perspective in *Science* stating that our ability to adapt agriculture would partly depend on acceptance of genetic improvement techniques, like genetically modified organisms (GMOs). Two years ago, much less a decade ago, we could not imagine the impacts of a global pandemic that compounded the need for a resilient food system (see CAST 2020a for a discussion).

Moreover, innovation in agricultural production is necessary to aid in combatting the negative effects of climate change and new pest and disease pressures that result from trade between geographical regions. Human behavior, and its influence on the climate, have caused a decrease in global agricultural efficiency by an estimated 21% since 1961 (Ortiz-Bobea et al. 2021). This is equivalent to losing seven years of production and future reductions in efficiency are anticipated to be greater for populations in warmer regions like Africa and Latin America. GMOs have the capability to increase nutrition security (De Moura 2016; Zimmermann and Qaim 2004), while also reducing land use (Brookes and Barfoot 2020a; Taheripour, Mahaffey, and Tyner 2016) and reliance on more toxic chemicals (Ahmed et al. 2021).

Bt crops were modified to protect plants from insects and herbicide-tolerant crops were modified to allow the plant to withstand specific herbicides so that competing weeds can be better controlled.

A framework for regulation of GMO plants and animals was established in the 1980s (OSTP 1986) and the first GMO food, a tomato, was sold to consumers in 1994 (FDA 2020). Commercialization of several other GMO crops occurred over the next several years, including the now largely adopted *Bacillus thuringiensis* (Bt) and herbicide-tolerant (HT) crops. Bt crops were modified to protect plants from insects and HT crops were modified to allow the plant to withstand specific herbicides so that competing weeds can be better controlled. By 1999, more than half of cotton and soybeans acres were planted to GMO varieties in the U.S. Presently, more than 90% of corn, cotton, and soybeans are planted to GMO varieties (USDA ERS 2020a). In 2013, there were more than 4,500 field release permits and notifications issued by USDA APHIS for GMO varieties with insect resistance, and more than 6,500 for those with herbicide tolerance (Fernandez-Cornejo et al. 2014).

The GM Rainbow papaya accounts for over 90% of papaya production in Hawaii.

While most commercialized GMO crops possess traits for either herbicide or pesticide tolerance, GMO applications can also provide resistance to viruses like the notable example of the Rainbow papaya. Papaya ringspot virus (PRV) was first detected in Hawaii in the 1940s and began affecting crop yields by the 1950s. By the late 1990s, PRV had affected every papaya producing region in the state, resulting in production dropping by over 50% between 1993 and 2006. The Rainbow papaya, a GMO papaya resistant to PRV, was commercialized in 1998 and within two years it accounted for over half of all papaya production in Hawaii. Ten years later, the Rainbow papaya accounted for over 90% of papaya production (Gonsalves and Gonsalves 2014). The story of the Rainbow papaya demonstrates how some pest problems can be very difficult, if not impossible, to control without genetic improvement. Thus, limiting GMO solutions would reduce the availability and quality of some foods in the marketplace (Van Esse et al. 2020).

Citizens and consumers have displayed resistance to GM technology.

Although GMO applications have provided tangible benefits throughout the food system (Ahmed et al. 2021; Qaim and Traxler 2005), citizens and consumers have displayed resistance to the technology which is counter to statements made by non-profit scientific societies (McFadden and Lusk 2015). The American Association for the Advancement of Science concluded:

> "...consuming foods containing ingredients derived from GM crops is no riskier than consuming the same foods containing ingredients from crop plants modified by conventional plant improvement techniques." (AAAS 2012).

The United States National Academy of Sciences, World Health Organization, and American Medical Association have also made similar statements about the safety of GMOs on human health (NRC 2004; WHO 2014; AMA 2014).

"… consuming foods containing ingredients derived from GM crops is no riskier than consuming the same foods containing ingredients from crop plants modified by conventional plant improvement techniques."
–AAAS 2021

The objective of this paper is to communicate the benefits of GMOs and the potential cost to society if the technology were removed from the marketplace. We blend results from academic research, public agencies, and statements from non-profit and scientific organizations to highlight the positive effects of GMO adoption. Much of the discussion is U.S. centric, simply because of the large-scale adoption of GMO crops in the U.S. When possible, we also discuss potential global impacts and the implications for less developed countries if GMOs were removed from the marketplace.

Benefits of GMOs to Consumers

Despite assurances from scientists, governments, and industry that GMOs are safe, many consumers are skeptical and even hostile towards the technology and the resulting food products (see Huffman and McCluskey 2014, for a discussion). Generally, about a third of consumers state that GMOs are not safe to consume (McFadden and Lusk 2015; McFadden and Lusk 2016). In a 2015 report, the UK Parliament's House of Commons stated:

> "We are each entitled to our own opinion and value-based opposition to genetic modification, or any other technology, is perfectly legitimate. However, this does not justify knowingly and willingly misinforming the public. We strongly urge those seeking to inform the public about genetic modification and other advanced genetic plant technologies to provide an honest picture of the scientific evidence base and the regulatory controls to which these products are currently subject. Where opposition to such technologies is value-based, this should be openly acknowledged and should not be concealed behind false claims of scientific uncertainty and misleading statements regarding safety." (HOC 2015)

This is a call to stop disinformation about GMOs, which unnecessarily heightens public risk perceptions. Although, citizens who are concerned about safety are not always receptive to information from scientific organizations stating that GMOs pose no more risk than non-GMOs (McFadden and Lusk 2015), nor receptive to information from interested parties (Huffman et al. 2007). Moreover, opponents are generally overconfident in their knowledge about GMOs (Fernbach et al. 2019). Taken together, these results suggest that debiasing citizens who have an inflated risk perception due to disinformation is an extremely difficult challenge for science communicators.

A major source of concern about GMOs is motivated by possible long-term consequences on human health (Siegrist, Connor, and Keller 2012). However, there have not been any scientifically documented human safety issues associated with food made from GMO raw materials that have been released for sale anywhere in more than 30 years of evaluation (NASEM 2016). Moreover, more than 4,400 science-based risk assessments undertaken since 1992 all concluded the risks from GMO crops were no different from the risks of non-GMO crops (ISAAA 2020).

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Further contradicting heightened concerns about negative health outcomes associated with GMOs is the evidence that GMO crops protect human health in some instances. For example, randomized trials in Bangladesh examined the impact of Bt brinjal (eggplant) on pesticide use and toxicity exposure for farmers; the study concluded that adopting Bt brinjal decreased pesticide costs by 38% and toxicity of pesticides applied by as much as 76% (Ahmed et al. 2021). This is relevant to consumers, too, as farmers maintain brinjal for consumption, and Bt adoption allowed those households to retain more brinjal for personal consumption because they were able to reduce yield loss, had less post-harvest waste, and thus collected higher net returns by an average of 128% (Ahmed et al. 2021). GMO cotton adoption in India and Pakistan reduced pesticide poisoning by an estimated nine million instance annually, and 45% of GMO cotton farmers in Pakistan reported no incidents of pesticide poisoning (Kouser and Qaim 2011; 2013). Analysis of GMO cotton adoption in Burkina Faso found similar reductions in the incidence of pesticide poisoning, with an estimated 30,000 fewer cases annually (Vitale, Vognan, and Ouattarra 2014). Additionally, Bt corn contains lower levels of naturally occurring fungal-derived carcinogens than non-Bt corn, on average, because of reductions in fungi that colonize non-GM corn at higher rates (Wu 2006). Certain mycotoxins are more likely to occur in less developed countries, and these are specific areas where Bt corn adoption may contribute to improving human health (Alshannaq and Yu 2017).

Adoption Bt brinjal (eggplant) decreased pesticide costs by 38% and toxicity of pesticides applied by as much as 76%.

Bt corn contains lower levels of carcinogenic chemicals than non-Bt corn, on average, because of reductions in fungi that colonize non-GM corn at higher rates.

As research increases into enhancing the nutritional composition of crops to embed nutrients in culturally accepted foods, limiting the ability of GMO technology to assist with genetic improvement is a blow to the nearly 820 million people presently without nutrition security. Increased nutrient availability in crops and food can reduce negative human-health outcomes like cancer, diabetes, cardiovascular disease and hypertension (Hefferon 2015). Additionally, access to food with higher nutrient content in the first few years of life has significant lifelong health benefits, such as the reduction in stunting and blindness (Wesseler et al. 2017; Dubock 2019). GMO crops can improve human health through applications that biofortify foods; although, the higher regulatory burden placed on GMOs have limited biofortified applications to conventionally bred crops (CAST 2020b; Garg et al. 2018) until recently.

GMO crops can improve human health through applications that biofortify foods.

A GMO application targeted at improving consumer nutrition, Golden Rice, received approval in the Philippines for commercial production in 2021 (IRRI 2021). Golden Rice is biofortified with beta-carotene, which is a precursor to vitamin A, and the golden color after milling comes from the accumulation of beta-carotene (Schaub et al. 2005). Access to foods high in vitamin A is critical to human health outcomes and, in 2019, 22% of children between 12 and 24 months had inadequate levels of vitamin A in the Philippines (Mbuya et al. 2021). In 2016, more than 100 Nobel laureates signed a letter calling for a stop to the opposition of GMOs, specifically

Golden Rice is biofortified with beta-carotene, which is a precursor to vitamin A.

referencing Golden Rice, and asked, “How many poor people in the world must die before we consider this a ‘crime against humanity’?” (Nobel 2016). Statistical simulations indicate that if Golden Rice is substituted for 70% of the currently consumed rice in the Philippines, the prevalence of vitamin A deficiency would decrease by 55–60% in women and approximately 30% in children (De Moura 2016), and an earlier study estimated the potential economic benefits of decreased disease burden in the Philippines associated with Golden Rice to range between $16 and $88 million USD per year (Zimmermann and Qaim 2004). Commercial production of Golden Rice represents an important first step towards realizing improvements in human health possible through GMO biofortification.

Another motivation of concern for some citizens is the potential market control given to companies that develop and patent GMOs. Perceived fairness about how benefits are distributed to producers and consumers is an important factor for GMO support (McComas et al. 2014). Table 1 shows results from 10 studies that estimated the distribution of benefits from GMO adoption in the United States. The estimated benefits focus on the extra net returns made available by the innovation and the value of reduced prices paid by consumers. Estimated benefits from GMO adoption ranged from $334 million to $1.5 billion annually; however, it is important to note that these studies were conducted when adoption rates were still relatively low (i.e., 1999 to 2005). Estimated benefits today are possibly orders of magnitude higher, given the significantly higher adoption rates. Depending on the study, biotech and seed companies obtained from 6% to 68% of the benefits created, farmers captured from 4% to 59%, and consumers were also projected to capture a relatively large fraction of the benefits, ranging from 5% to 57% because of lower food prices.

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				Distribution of Benefits to:			
Study	*Trait and Commodity*	*Year Studied*	*Total Benefits from Innovation (million USD)*	*U.S. Consumers*	*U.S. Farmers*	*Biotech and Seed Companies*	*Rest of the World*
Price et al. 2003	HT cotton	1997	$230	57%	4%	6%	33%
Price et al. 2003	BT cotton	1997	$210	14%	29%	35%	22%
Price et al. 2003	HT soybeans	1997	$310	5%	20%	68%	6%
Falck-Zepeda et al. 1999	BT cotton	1998	$213	7%	46%	44%	4%
Falck-Zepeda et al. 2000a	BT cotton	1997	$190	7%	43%	44%	6%
Falck-Zepeda et al. 2000b	BT cotton	1996	$240	9%	59%	26%	6%
Moschini et al. 2000	HT soybeans	1999	$804	10%	20%	45%	26%
Sobolevsky et al. 2005	HT soybeans	1999	$1,577	26%	25%	49%	n/a
Wu 2002	BT corn	2001	$334	10%	50%	31%	9%
Qaim and Traxler 2005	HT soybeans	2001	$1,230	53%	13%	34%	n/a

Table 1. Ten Studies on the Benefits from Early Adoption of Biotech Traits in the United States. Note: Because of the rounding of percentages, some rows do not total exactly 100%.

To further summarize the findings, Figure 1 presents the estimated percentages that provided the best fit to the data from the studies listed in Table 1, given the constraint that percentages had to sum to one. Across all the commodities and studies, the estimates suggest about 38% of the benefits flowed to the innovators, with U.S. farmers and landowners capturing the next highest share of benefits at 31%. Next were consumers followed by farmers outside the United States. An important implication of these studies is that non-GMO foods are more costly than GMO counterparts. GMOs have contributed to reducing the real cost of food (Stebbins 2016), and consumers would face higher prices if GMO options were removed. Using scanner data from retailers, estimated premiums for non-GMO products ranged from 9.8% to 61.8% and premiums for organic, which is implicitly non-GMO, ranged from 13.8% to 91% (Kalaitzandonakes et al. 2018); these are results across four categories (cooking oils, tortilla chips, breakfast cereals, and ice cream) from 2009 to 2016. Banning GMO corn and soybeans would increase corn prices, in the United States, from 4 to 17% and soybean prices increasing from 1% to 10%, and when accounting for inflexibility in trade and food consumption these price increases rise to 28% and 23% for corn and soybeans, respectively (Taheripour, Mahaffey, and Tyner 2016). These types of corn and soybeans are typically used for livestock feed but are also used to derive food ingredients. So, these commodities make up a small proportion of the overall food basket for consumers and the increases in corn and soybean prices translate to a much smaller food increase for consumers, ranging from 0.2 to 1.0%. However, while these numbers may seem small, a 1% increase in food prices translates to $14 billion per year and welfare losses per year ranging from around $200 million to about $4.9 billion for the U.S. economy; global welfare losses ranged from around $800 million to about $5.9 billion (Taheripour, Mahaffey, and Tyner 2016). Thus, increased costs are likely greater for some countries that can least afford to absorb additional costs.

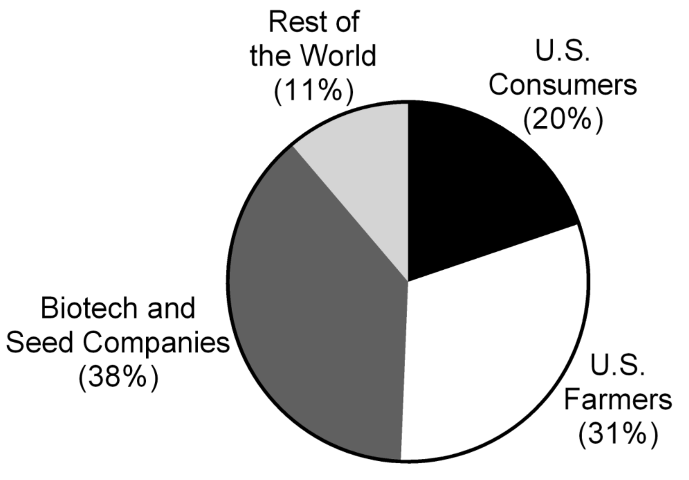

Figure 1. Distribution of Benefits from Early Adoption of Biotech Traits in the U.S. (source: Table 1)

Non-GMO foods are more costly than GMO counterparts.

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Differences in GMO regulation across applications and countries creates a bottleneck in development and commercialization that ultimately reduces food security (Steinwand and Ronald 2020). It is worth noting, GMO adoption in only a subset of countries can benefit consumers in other countries by boosting international food trade which lowers the world price of food, feed, and fiber (Hertel, Baldos and Fugle 2020; Nes, Schaeffer and Scheitrum 2021). Thus, GMO adoption reduces world prices so that even countries that ban the importation of GM products can benefit from overall lower prices; although, the benefits are lower for countries that restrict their own production of GM foods (Anderson 2010).

The long-term effects of GMOs on the environment are another source of concern for consumers (Siegrist, Connor, and Keller 2012). However, in a 2013 report, the European Academies Science Advisory Council stated:

Differences in GMO regulation across applications and countries creates a bottleneck in development and commercialization that ultimately reduces food security.

> “There is compelling evidence that GM crops can contribute to sustainable development goals with benefits to producers, consumers, the environment and the economy…Capturing these benefits in agricultural innovation should be a matter for urgent attention by EU policymakers.” (EASAC 2013).

More discussion about the impact of GMOs on the environment is provided in the following section.

Benefits of GMOs to the Environment

Concerns about the environmental impacts of GMOs have motivated the destruction of field trials used to generate the data required for risk assessments necessary to commercialize GMO crops (Moore and Applegate 2020). An environmental activist who previously took part in destroying field trials became a GMO advocate after reviewing scientific evidence, and now believes that the technology can decrease the environmental impacts of farming (Lynas 2013). Adoption of innovations in animal and crop genetics, chemicals, equipment and farm organization by U.S. agricultural producers over the past several decades increased their efficiency by almost 200% (Njuki 2020; USDA ERS 2020b).

Agriculture is the largest user of habitable land and GMO crops make more efficient use of land by protecting agricultural yields from pests, which often results in higher yields than non-GMO counterparts.

Agriculture is the largest user of habitable land and GMO crops make more efficient use of land by protecting agricultural yields from pests, which often results in higher yields than non-GMO counterparts (NASEM 2016). For example, adoption of GMOs has provided additional yields for corn, soybeans, and cotton (Brookes and Barfoot 2020a; Barrows, Sexton, and Zilberman 2014). Removal of GMO corn in the U.S. would require an increase in land-use larger than the expansion in land-use that resulted from the ethanol program’s goal of an increasing production from about 3.5 billion to 15 billion gallons (Taheripour, Mahaffey, and Tyner 2016). A study of global changes in land-use from the commercialization of GMO crops up to 2018 estimated that an additional 12 million hectares of soybeans and 8 million hectares of corn would have needed to have been planted to replace the production provided by GMO crops (Brookes and Barfoot 2020a). Areas of land designated for other use would have to be brought into production to supply the needed cropland and approximately one-third of the needed land could come from forest areas (Taheripour, Mahaffey, and Tyner 2016). Demand for commodities beyond the typical uses require an expansion in land-use, like the U.S. ethanol program. GMOs also allow farmers in some geographical locations, like Argentina and Paraguay, to plant a second crop in the same growing season due to shortened production cycle (Brookes and Barfoot 2020a), which also reduces pressure to expand land-use for agricultural production.

An additional 12 million hectares of soybeans and 8 million hectares of corn would have needed to have been planted to replace the production provided by GMO crops.

GMO crops can also reduce producer reliance on pesticides and limit the negative externalities associates with pesticide use. For example, a recent study estimated that the cumulative reduction in pesticide use due to GMO adoption between 1996 and 2018 has reached 775 million kg of active ingredients and lowered the environmental impact of chemicals used by 18% globally (Brookes and Barfoot 2020b). An older study synthesized results from 147 studies conducted in developed and developing countries to estimate the impact of GMO adoption on pesticide use and concluded that, on average, GMO crops were associated with a 37% decrease in pesticide use and a 39% reduction in pesticide costs (Klümper and Qaim 2014). If GMO crops were removed from the set of options for farmers, pesticide use and the toxicity of pesticides applied would increase. Bt crops have successfully reduced the amount of insecticide applied to corn and cotton crops (NASEM 2010).

If GMO crops were removed from the set of options for farmers, pesticide use and the toxicity of pesticides applied would increase.

Estimates show that GMO corn adoption from the 1990s to 2010 caused a 90% decrease in insecticide use (Miranowski and Lacy 2016; Fernandez-Cornejo et al. 2014). Additionally, the benefits of adopting Bt crops spillover to nearby non-Bt growers because the reduced insect population also protects the yield of non-adopters (NASEM 2016).

GMO corn adoption from the 1990s to 2010 caused a 90% decrease in insecticide use.

There does not appear to be a strong link between HT crops and changes in herbicide use (Fernandez-Cornejo et al. 2014; Klümper and Qaim 2014). Some research has shown that herbicide use associated with HT crops has increased over time (NASEM 2016; Perry et al. 2016a), while other research identified a 30% reduction in herbicide use in crops following HT canola (Smyth et al. 2011). While the evidence for changes in herbicide use associated with HT crop adoption is mixed, the discussion about toxicity exposure is more nuanced than solely focusing on the amount of herbicide applied. HT crops allow farmers to reduce toxicity exposure by substituting to a relatively less toxic herbicide (Kleter et al. 2007; NRC 2010), and higher levels of toxicity increase the negative impact of agricultural production on the environment (Kovach et al. 1992).

Delayed adoption of GMO canola in Australia from 2004-2014 resulted in the application of an additional 6.5 million kg of chemicals, a 14% higher environmental impact; 7 million additional field passes for application, requiring an additional 8.7 million liters of diesel; totaling 24 million kg more GHGs being released.

Non-GMO adopters sometimes mix several different herbicides as an improved form of weed control, which likely has a higher cumulative environmental impact. In Western Canada, for example, GMO canola grown reduced the environmental impact of chemical use associated with weed control by 53% relative to non-GMO canola (Smyth et al. 2011a). Delayed adoption of GMO canola in Australia from 2004-2014 resulted in the application of an additional 6.5 million kg of chemicals, a 14% higher environmental impact; 7 million additional field passes for application, requiring an additional 8.7 million liters of diesel; totaling 24 million kg more GHGs being released (Biden et al. 2018). These results bring attention to the fact that the impacts on the environment from not adopting GMO crops go beyond just the amount of pesticide used and include factors like higher fuel use needed for increased applications of pesticide.

The effective weed control provided by HT crops, and the ability to use glyphosate, has allowed producers to eliminate tillage from land management practices.

Prior to the commercial release of GMO crops in the mid-1990s, in-crop weed control options and efficacy were less than that of today. Some herbicides of the 1970s and 1980s often required soil incorporation prior to seeding, with in-crop herbicides providing limited control of grassy weeds and difficult to control weeds (Smyth et al. 2011b). Ineffective weed control caused farmers to rely on tillage practices as the leading option for weed control. The effective weed control provided by HT crops, and the ability to use glyphosate, has allowed farmers to eliminate tillage from land management practices. In some cases, HT crop adoption provides weed control from one year to the next that allows some farmers continually practice zero tillage (Sutherland 2021). Reduced tillage has also been reported in all major GMO crop producing countries, including Argentina, Australia, Brazil, Canada and the United States (Brookes and Barfoot 2020a).

Reduced tillage contributes to reducing the influence of agricultural production on climate change in two ways. One, fewer GHGs are released during the production of a crop, as each pass when tilling for weed control releases carbon into the atmosphere while also making soils more susceptible to wind and water erosion (Smyth et al. 2011a). Farmers in Western Canada who adopted GMO canola reduced soil erosion and by an estimated 83% because of conservation tillage practices (Smyth et al. 2011b). Secondly, conservation tillage practices allow for ongoing carbon dioxide (CO_2) sequestration. In 2018 alone, the estimated reduction in GHG emissions associated with the global adoption of GMO crop was equivalent to removing over 15 million vehicles from the road for one year (Brookes and Barfoot

2020b). While the sum effects will vary by location, there is evidence from Saskatchewan, Canada indicating that GMO adoption transitioned crop agriculture from a net GHG emitter to net sequester (Awada and Smyth 2018). If GMO crops were removed from production, farmers would be required to return to tillage as a major form of weed control. This could increase GHG emissions to a point where crop agriculture was no longer capable of net GHG sequestration.

Around a third of bananas are grown in sub-Saharan Africa and banana wilt has caused 100% yield losses for some producers. However, several GMO bananas have shown 100% resistance to banana wilt in field trials.

A positive aspect of GMO crops that is infrequently mentioned is the potential for the technology to reduce negative impacts on ecology and ensure that food crops that are presently threatened can be preserved. Adoption of HT and Bt corn in the U.S., reduced the impacts of chemicals on fish, birds, bees, and beneficial arthropods; although, the same was not true for HT soybeans (Perry et al. 2016b). Plant diseases can have devastating impacts on food production, for example, banana wilt and citrus greening. Around a third of bananas are grown in sub-Saharan Africa and banana wilt has caused 100% yield losses for some farmers (Blomme et al. 2014). However, several GMO bananas have shown 100% resistance to banana wilt in field trials (Tripathi et al. 2014). The U.S. citrus production is continuing to battle citrus greening, a disease that caused $7.8 billion in losses from growing seasons 2006–2007 to 2013–2014 (Hodges et al. 2014), and consumers are supportive of biotechnological solutions for citrus greening (McFadden et al. 2021).

The ability to ensure that endangered plant species may be restored through biotechnology offers a substantial public and consumer benefit.

Biotechnology has offered a solution for the American chestnut tree, which was essentially eliminated by disease (Kuhlman 1978). A GMO chestnut tree was developed that are resistant to the blight and are presently undergoing risk assessment (Grant 2020). The ability to restore plant species is being viewed as promising by some environmental non-governmental organizations, that had been firmly opposed to GMO crops. In 2021, the Sierra Club publicly announced that GMO chestnut trees provide an environmental benefit (Bailey 2021). The ability to ensure that endangered plant species may be restored through biotechnology offers a substantial public and consumer benefit.

Disease, insects, and weeds reduce yield and GMO crops reduce damage so that crops have an improved chance of reaching maximum yield potential.

Benefits of GMOs to Crop Producers

In the U.S., more than 90% of corn, cotton, and soybeans are currently planted to GMO varieties (USDA ERS 2020a). Given the high level of GMO adoption by U.S. crop farmers, the benefits of using the improved seed must outweigh the costs. Benefits of adoption could include protecting crop yield or decreasing production costs, or both. While the specific reasons for adoption likely vary across farmers, most farmers that have adopted Bt and HT crops have done so to protect crop yield (Fernandez-Cornejo et al. 2014). Disease, insects, and weeds reduce yield and GMO crops reduce damage so that crops have an improved chance of reaching maximum yield potential. For example, Bt crops protect yield from insects and HT crops protect yield from competing weeds. The second most-selected reason for producer adoption of Bt and HT crops was saving time and making management practices easier; except for HT soybeans, for which decreasing input costs associated with pesticide use was the second most-selected reason for adoption (Fernandez-Cornejo et al. 2014). Concern about resources required for production is understandable from the prospective of a producer, as resources are costly, can be difficult to procure, and impact net revenue.

GMO crops that have more than one GMO trait, for example a crop that is *both* Bt and HT, are referred to as having stacked traits. GMO crops with stacked traits have higher yields than conventional seeds or GMO seeds with only one trait, and most of the corn and cotton acres in the U.S. are planted with stacked seed (Fernandez-Cornejo et al., 2014). There is substantial evidence that Bt crops protect yield from losses due to insects (Fernandez-Cornejo et al. 2014), and the relative difference in yield between GMO and non-GMO crops can occur during unfavorable conditions, which reduces production risk in a bad year (Chavas et al. 2014). Additional to the direct benefits for adopters, non-Bt farmers in areas with high Bt adoption also benefit through reduced insect population (NASEM 2016). For example, non-Bt corn growers received 75% of the estimated cumulative benefits associated with pest suppression from Bt corn adoption in the three states considered (i.e., Illinois, Minnesota, and Wisconsin) (Hutchison et al. 2010). A 2014 article (Klümper and Qaim) examined results from 147 studies that estimated the global impact of adopting GMO corn, cotton, and soybeans on yields, net returns, and pesticide use. On average, yields increased by 22%, pesticide use decreased by 37%, and net revenue increased by 68%, with farmers in developing countries receiving relatively higher increases in yield and net return (Klümper and Qaim 2014).

The estimated global impact of adopting GMO corn, cotton, and soybeans on, average, increased yields by 22%, decreased pesticide use by 37%, and increased net revenue by 68%.

While there is considerable evidence that GMO technology protects yield, whether the seed enhancement increased yield potential above previous year-over-year trends is a more nuanced question. Prior to the commercialization of GMOs, improvements in crop genetics, access to synthetic fertilizers, and improved farm machinery provided year-over-year increases in yield (Edgerton 2009). However, annual growth in global yields have decreased (Alston, Beddow, and Pardey 2009) and changes in yield have become stagnate in some areas (Ray et al. 2012). Although there is ample evidence that GMOs protect yield, there has been skepticism about whether the crop protection contributes to annual growth rates above previous those associated with traditional agronomic and genetic improvement (Hakim 2016).

Teasing out the yield effects from crop improvements is straight forward when considering a small geographic area. However, it is difficult to tease out impacts on yield for large geographical areas because factors, like weather, vary with the area considered. Without controlling for varying factors within a geographical area, it is not clear what is causing changes in yield. Lusk, Tack, and Hendricks (2019) used county-level data on corn yields and weather for 13 U.S. states from 1980 to 2015 and concluded that GMOs did not increase yield in the absence of controlling for weather; however, GMO corn was associated with a 17% increase in yield potential after controlling for weather events across the area considered. Depending on costs of production and commodity prices, increases in yield can translate into an increase in net returns. Global adoption of GMOs provided $225 billion net economic benefits at the farm level from 1996 to 2018 (Brookes and Barfoot 2020a), and developing countries receive relatively higher increases in net revenue (Klümper and Qaim 2014).

Global adoption of GMOs provided $225 billion net economic benefits at the farm level from 1996 to 2018.

Adoption of HT soybeans is associated with decreases in household labor and increases in off-farm income, thereby increasing total household income.

GMO crops reduce the time farmers spend on-farm and the time saved is a benefit not typically reflected in traditional calculations of net returns (Fernandez-Cornejo and McBride 2002), yet farmers place a high value on the time saved and convenience of GMO crop adoption (Marra and Piggott 2006). Recall that saving time and making management practices easier was a major reason for producer adoption of GMOs (Fernandez-Cornejo et al. 2014). Producer desire to reduce time on-farm is not surprising, as that time can be reallocated to generate off-farm income, spend time with family, or leisure. Adoption of HT soybeans is associated with decreases in household labor (Gardner et al. 2009) and increases in off-farm income, thereby increasing total household income (Fernandez-Cornejo et al. 2005). The relationship between Bt crops and time savings are not as apparent as HT crops, at least in the U.S., and may hint that adoption of Bt crops is due to other factors like decreased pesticide use. Because of increases in yield, GMO adoption can increase labor needs when crops are manually harvested. For example, increased yields received by Bt cotton adopters in India actually increased labor needs due to increased yield; however, adopters received a higher return on the increased labor and household income more than doubled for vulnerable farmers (Subramanian and Qaim 2010).

In the U.S., the majority of GMO corn and processed soybean meal are used to feed livestock, so the increased demand for animal products will increase demand for corn and soybeans.

Benefits of GMOs to Livestock Producers

Per capita demand for meat and milk, along with population size, are expected to increase globally (Alexandratos and Bruinsma 2012). In the U.S., feed accounts for 60% to 70% of total costs for livestock farmers (Lawrence et al. 2008) and the majority of GMO corn and processed soybean meal are used to feed livestock (Paarlberg 2014), so the increased demand for animal products will increase demand for corn and soybeans. Mold can develop in feedstuffs and create mycotoxins, which are poisonous defensive chemicals that pose serious health and economic threats worldwide. Mycotoxins are found in animal feeds, human foods, animal products, and soil (Tola and Kebede 2016), and are toxic to animals if ingested at high levels. Negative health outcomes for animals ingesting mycotoxins at high levels include reduced body weight and fertility, immune suppression, increased susceptibility to diseases and parasites, liver and kidney damage, tumors, and death (Oswald and Coméra 1998). Public awareness of mycotoxin-related health risks is limited and the benefits of Bt crops for reduction of mycotoxin levels have been under appreciated in global policies (Wu 2007).

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The most significant agricultural mycotoxins are fumonisins and aflatoxins. Higher rates of esophageal cancer have been associated with human consumption of fumonisins in developing countries (Marasas et al. 2004) and among marginalized communities in developed countries (Sydenham et al. 1991). Fumonisins are linked to equine leukoencephalomalacia, a central nervous disease, and the typically fatal porcine pulmonary edema. Aflatoxins are potent liver carcinogens (Wu 2006) and in chickens, can result in decreased egg production and inferior eggshell quality (Wyatt 1991). In ruminants, aflatoxin consumption can result in reduced milk, meat, and wool production and can pass into milk if cows consume contaminated grain (Hussein and Brasel 2001).

Losses associated with mycotoxins have considerable economic impacts (Miller and Marasas 2002) and international trade of commodities at high risk of mycotoxin contamination can be significantly affected by regulations enforced by importing countries (Marin et al. 2013). The impacts of mycotoxins are critical for developing countries that are often forced to export their best quality commodities and retain the lower quality commodities for domestic use, increasing risks for vulnerable populations (Wu 2006). The Food and Agriculture Organization (FAO) estimated that 25% of global food and feed is affected by mycotoxins (FAO 2004) and climate change is expected to further increase the incidence of mycotoxins (Battilani et al. 2016).

It is known that Bt corn can reduce insect damage with the secondary effect of reducing fumonisin levels compared to non-Bt counterparts.

It is known that Bt corn can reduce insect damage with the secondary effect of reducing fumonisin levels compared to non-Bt counterparts (Wu 2007; Bowers et al. 2014; Bánáti et al. 2017). Bt corn is estimated to lower concentrations of fumonisin by 31% (Pellegrino 2018); although, the effect of Bt to reduce aflatoxin contamination levels is inconclusive (Abbas et al. 2013; Ostrỳ et al. 2015). In the absence of Bt crops, countries that have stringent requirements for mycotoxin levels would not be able to meet them and would have to pay more for higher quality foods (Masip et al. 2013). Although mycotoxin levels are dependent upon multiple factors such as insect activity, genetic background of the crop, and environmental conditions, reductions resulting from the Bt trait are seen frequently enough globally, with no documented harm, that Bt insect-protected crops play a role in global food safety and livestock health. New developments in biotechnology, such as drought resistance, could also be coupled with insect resistance to further address the issue of increasing mycotoxin levels as a result of a changing climate.

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Realized and Potential Costs of Restricting GMO Applications

The slow and unpredictable pace of GMO crop regulatory approval and commercialization is limiting investment in research and development. A survey of companies responsible for 95% of all new GMO traits introduced in EU and the U.S. estimated that the average costs associated with regulatory science, registration, and affairs to get a new trait introduced was $35 million between 2008–2012, and in 2011 this process took, on average, over nine years (McDougall 2011). These regulatory hurdles essentially largely preclude public institutions from obtaining approval for GMO applications, and the private sector has reduced investment in areas with strict regulation.

Strict regulation of GMO crops in the EU has driven $250 million in R&D investment out of the EU over the past 30 years.

A survey of EU producers estimated that more than one-third of producers were likely or very likely to adopt GMOs, citing reduction of weed control costs and higher income as motivations for adoption.

The EU has largely forbidden farmers from growing crops containing gentically modified traits, but allowed the importation of GMO crops and their derivatives (Tagliabue 2016). Strict regulation of GMO crops in the EU has driven $250 million in R&D investment out of the EU over the past 30 years; in the 1990s, the EU accounted for one-third of global agricultural R&D investments and by 2014 this had dropped to 8% (Smyth 2017; McDougall 2013). BASF halted investment in GMO crops developed for growing conditions in the EU after developing a potato with resistance to the disease late blight (Dixelius, Fagerström, Sundström 2012) and publicly acknowledged this would lead to a loss of 140 jobs in the EU, while unconfirmed industry reports later placed the number closer to 900, most of which were highly trained scientists. A survey of EU producers estimated that more than one-third of producers were likely or very likely to adopt GMOs, citing reduction of weed control costs and higher income as motivations for adoption (Areal, Riesgo, and Rodríguez-Cerezo 2011). Some EU producers are calling for a streamlined approval process of GMOs; however, possible adopters may still be hesitant to plant approved GMO crops due to additional administrative requirements (FSN 2012).

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Trade barriers targeted at GMOs reduce access to food, limit farm revenues, and increase overall prices. When countries lift trade barriers, it was estimated that imports would increase by an estimated 14.7% which result would result in an estimated 4.86% reduction in food prices; conversely, a trade barrier decreases access to imports by almost 10% and food prices increases by 1% (Nes et al. 2021). Regulatory barriers have important implications for global food security, and many of the countries that have not adopted GMOs are among the world's least food secure and most reliant on imports as a source of food (Nes et al. 2021). Although 2016 global production of GMO crops generated an estimated $57B in farm-gate revenues, widespread approval of GMOs would generate an additional $65 billion if crops were adopted at similar rates where adoption is possible -- with developing countries receiving the majority of additional revenue (Scheitrum, Schaefer, and Nes 2020).

While GMOs have been widely adopted in the United States, the National Bioengineered Food Disclosure Standard requires food companies to label foods derived from GMOs by January 1, 2022 (USDA AMS 2018). The policy was a source of uncertainty when it was established because which products would require a label and the threshold for segregation mishaps were yet to be decided (McFadden 2017; McFadden and Malone 2018). Ultimately, the threshold for segregation mishaps was set at no more than five percent (5%) of the specific ingredient (USDA AMS 2018). Penalties for segregation mishaps increase both the cost and risk of adopting GMO technology, and segregation may be extremely difficult for widely grown commodities like corn and soybeans (Zilberman et al. 2018). A 2012 mandatory labeling ballot initiative in California would have increased costs for in-state food processors by an estimated $1.2 billion (Alston and Sumner 2012). Some of the costs from mandatory labeling polices would be transferred to consumers, and it was estimated that a mandatory label in New York would have increased annual household food expenditures by approximately $224 per year for a family of four (Lesser and Lynch 2012). Although, estimates from scanner data indicate that associated costs could be orders of magnitude higher (Kalaitzandonakes et al. 2018).

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When asked, consumers typically indicate support for mandatory labels on GMOs; however, consumers also indicate support for mandatory labels for food containing DNA (McFadden and Lusk 2016). The fact that consumers also want a mandatory DNA label suggests that simply asking someone if they want something may not always be a reliable measure to motivate policy, as it is completely rational to say “yes” to free information that may or not be valuable and is not accompanied by a cost. Consumers who are uncertain about the motivation of mandatory GMO labeling may incorrectly assume the label was motivated due to possible safety concerns (Bar-Gill, Schkade, and Sunstein 2019). Although, when a mandatory labeling policy was implemented for a short period in Vermont, attitudes toward GMOs improved in that state (Kolodinsky and Lusk 2018).

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GMO labeling is unlikely to provide context to consumers and may deceptively influence purchasing decisions. For example, consumers may pay premiums for food labeled non-GMO even when there is no existing GMO alternative, as is the case for non-GMO labeled salt (Wilson and Lusk, 2020). There is evidence that GMOs can be desirable to consumers if the benefits are mentioned, particularly if the benefits are targeted at consumers (Lusk, McFadden, and Rickard 2015). Consumers may pay a premium for GMOs if the GMO application provides a benefit to the consumer (e.g., Bugbee and Loureiro 2003; Lusk 2003) or reduces reliance on sensitive feedstuffs like wild fish stocks (Weir 2019). Given that consumers are concerned about GMOs while also having low levels of knowledge about GMO, and perhaps genetics in general, it is not surprising that information can significantly influence purchasing decisions (Lusk et al. 2004; Rousu et al. 2007).

Conclusions and Looking Towards Gene Editing Technologies

Technological advancement in agricultural production has allowed humanity to increase the amount of food produced and more consumption of agricultural products in non-food uses while conserving the environment and resources. Continued advancements in production have allowed the U.S. to maintain a surplus in agricultural trade (USDA ERS 2020c) while, as a sector, emitting less than half the greenhouse gases of the global average associated with agricultural production (US EPA 2020a; US EPA 2020b). GMOs use less land, energy, and chemicals (Paarlberg 2020), and the carbon footprint of agriculture would certainly increase without GMOs. It is important that these

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results be considered in public discussion of the social and economic value of GMO technology.

Differences between GMO and non-GMO counterparts represent differences in costs, yield protection, and overall efficiency, which could continue to grow if the technology is not blunted. Certainly, the economic benefits from GMO crops are crucial, as without economic benefits for adopters, the technology would not have lasted for very long. Producers who currently grow GMO crops will likely suffer if nudged towards adopting non-GMO alternatives, because those producers have developed expertise in what they currently grow (Kalaitzandonakes and Magnier 2016).

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As the technologies used in plant breeding shift from gene insertion genetic modification to targeted gene deletion or mutation, crop and food production are on the verge of a significant revolution. Targeted and controlled mutagenesis is increasingly being used by plant breeders, both public and private, particularly when it comes to the application of the gene editing (GnEd) technologies (Gleim et al. 2020). The use of GnEd is providing phenomenal experimental yield increases, such as 20% for rice (Chen et al. 2020) and 200% for sorghum (Gladman et al. 2019). The technology is also being used to enhance the ability of plants to photosynthesize, increasing the amounts of CO_2 that a plant is capable of sequestering while also increasing yield (Kromdijk et al. 2016). GnEd has the potential to significantly improving food and nutrition security (Asanuma and Ozaki 2020; Lassoued et al. 2019).

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While GE crops have been, or are close, to commercialization in Argentina, Australia, Canada, Japan and the United States, the EU continues to struggle in how to regulate agricultural innovation (Smyth 2019). In 2018, the Court of Justice of the EU ruled that GnEd crops must be regulated within the EU's GMO regulations; thus, GnEd crops will be regulated like GMO crops. This ruling contradicts the EU's Farm to Fork strategy that aims to provide nutrition security, lower the environmental impacts of agriculture, and increase biodiversity. Immediately after the ruling, large and medium-sized agricultural technology firms announced they were relocating all agricultural R&D capacity developing GnEd applications (Smyth 2019). The scientific community responded by encouraging revisions to the EU regulations of GnEd application, and calls for a revised framework is perhaps best reflected by the European Commission's Group of Chief Science Advisors, which recommended:

> "…revising the existing GMO Directive to reflect current knowledge and scientific evidence, in particular on gene editing and established techniques of genetic modification. This should be done with reference to other legislation relevant to food safety and environmental protection." (EC 2019).

Furthermore, there is evidence, in the United States at least, that consumers are supportive of GnEd applications to reduce the prevalence of agricultural diseases like citrus greening (McFadden et al. 2021), and consumers in Canada may be more accepting of GnEd applications compared to GMOs (Muringai, Fan, and Goddard 2020).

GMOs are not a silver bullet and need to be combined with good agronomic practices and future innovations. However, without GMO crops as a part of the global cropping systems and food production, the second of the 17 Sustainable Development Goals of the United Nations, to end hunger, achieve food security and improved nutrition and promote sustainable agriculture, will be compromised. Within the span of 25 years since their first widespread commercial adoption, GMO crops have transformed cropping production systems in the places where the technology has been used and contributed to

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better pest and weed control, facilitated the adoption and maintenance of reduced and no tillage agriculture which have helped reduce levels of soil erosion, increased soil moisture conservation, improved soil health and reduced levels of greenhouse gas emissions. Without continued innovation and adoption of biotechnology like GMOs, the future of reducing food insecurity becomes an increasingly remote and unlikely scenario.

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