BIOTECHNOLOGY AND FOOD SECURITY

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Genetically engineered (GE) foods apply new molecular technologies to agriculture. Widely adopted in the United States, Brazil, and Argentina for the production of corn, soybeans, and cotton, they are practically banned in Europe and tightly regulated throughout the world. We have found that GE foods have significantly increased supplies of corn, soybean, and cotton, and lowered their prices, thus improving food security. GE foods have already contributed to a reduction in the use of pesticides and emissions of greenhouse gases. We show that expanded adoption of GE foods can further enhance food security and adaptation to climate change. Sound redesign of regulation will increase investment in GE varieties and help to allow development of new traits that will further improve human welfare.

The global human population has increased sevenfold from one billion to seven billion people since 1850. At the same time, food availability per capita has increased and the amount of land area used for farming has tripled, but farming captures a smaller share of the global workforce.[1] Gradual agricultural production intensification through increased reliance on the use of synthetic inputs like fertilizer and pesticides and the increased use of irrigation have led to these trends.[2] Yet, despite the abundance produced by modern agriculture, a large percentage of the global population remains vulnerable to food shortages.[3]

There are a variety of reasons for food shortages, ranging from effects from weather to economic and political shocks, all of which pose risks of potential malnourishment and starvation to populations.[4] The combined trends of popula-

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tion growth and increases in income will cause unprecedented increases in food demand that will challenge agricultural production.[6] Additionally, the transition away from non-renewable fuels and other sources of non-renewable raw materials may challenge agriculture to expand its range of production to include products such as biofuel and biochemicals as sources of fuel.[7]

In order to meet these challenges, society needs to establish the institutions and research capacity necessary to reduce reliance on petrochemicals. Such capacity can be achieved through the formation of a bioeconomy in which agricultural and renewable resource production provide fuel and fine chemicals.[8] One aspect that is emphasized here is the crucial role of agricultural biotechnology, especially in the context of food security. Through research and innovation, agriculture is undergoing processes of improved adaptation, with the aim of increasing productivity while reducing the environmental side effects of production. While the use of biotechnology is controversial, we will argue that these tools have already improved the global food situation by increasing supply and reducing prices. Furthermore, policy reforms that avoid banning these technologies, weigh the risks and benefits of regulating these new technologies, and further invest in research can contribute to expanding the food supply for global populations.

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The first section of this paper will define and address the challenge of food security in the context of sustainable development. The second section will provide an overview of agricultural biotechnology and its accomplishments thus far. The third section will address some of the impacts of genetic engineering (GE) technology on resources, health, and the environment. This will be followed by a discussion of policy reforms that can improve GE utilization in the future and recommendations for next steps.

Food Security and Sustainable Development

Two of the major objectives of resource policy design are to enhance food security and pursue sustainable development. The best way to look at food security is through a reduction in food *insecurity*, which is the probability that individuals will suffer a negative outcome due to a lack of available food.[9] Food security can be increased in two ways: by enhancing productivity and increasing access to food for individuals.[10] The enhancement of productivity leads to increased overall food supply, thus reducing food prices. Productivity is especially important in areas not well-linked to the global food supply chain. Many of these regions do not have the ability to import food commodities, and thus depend primarily on their own production. Insufficient road infrastructure tends to increase the price of imported inputs like fertilizer and reduce access to food during food supply crises.[11] Improving access to food can be achieved by building proper infrastructure, including roads and airports. It can also be achieved through institutions, e.g., by establishing insurance schemes or emergency relief programs.[12]

However, recent research suggests that a proper definition of food security has multiple dimensions: it is not only the provision of more food, but the provision of *healthier* food that includes vitamins and micronutrients. Biotechnology can enhance the quality of food by introducing micronutrients like vitamins and beta-carotene into food, and can increase the overall productivity, affordability, and quality of food.[13] Quality has already been enhanced to a large extent with certain commodities, but as we argue later, biotechnology has the potential to provide a means of production to vulnerable populations to facilitate an increase in food productivity under adverse conditions and poor states of nature.[14]

Biotechnology plays a large part in the pursuit of sustainable development.[15] Sustainable development aims to maximize human well-being over time, subject to environmental constraints.[16] Policies promoting sustainable development recognize the long-term environmental costs of production activities, and attempt to control and reduce them. Sustainable development addresses the vulnerability associated with dependence on non-renewable resources, while emphasizing the need for adaptation.[17] The notion of sustainable development has to be considered within a dynamic environment where evolution occurs, with organisms adapting to changes in external conditions. Human activities affect natural evolution, and creators of sustainable development policies have to recognize this coevolution in the design of those policies.

One particular source of environmental concern is climate change, which may become a major cause of food insecurity.[18] As climate change occurs, agricultural productivity in certain regions will decline, especially in regions closer to the equator, while regions closer to the poles will see productivity increase.[19] As a consequence, those regions undergoing productivity losses due to climate change may suffer from high food insecurity, which is especially troubling given that many countries in this region are already food insecure.[20]

Adaptation to climate change should include several elements: mitigation that reduces greenhouse gas (GHG) emissions, thus slowing climate change; innovation and development of new technologies; adoption and adaptation of existing technologies and crop systems in new locations; improved trade; and immigration.[21] Biotechnology plays a crucial role in the development of new technologies and local adaptation to change. The challenge in the development of a new technology is the time it takes to introduce it, but biotechnology can accelerate the development of new products, as well as the modification of crop systems.[22]

Agricultural Biotechnology and its Contribution

Agricultural biotechnology applies the tools of modern molecular and cellular biology to agricultural production—results of the breakthrough knowledge obtained by the discovery of the genome and DNA in the 1950s. One of the consequences has been the development of GE. For example, the new set of tools developed as a result of these discoveries has been utilized intensively in medication, with many modern medicines being GE pharmaceuticals. In addition, there are several important applications of molecular biology in agriculture, including market-assisted selection and in vitro propagation.[23] We will concentrate on agricultural GE technology, which is one of the most controversial biotechnology strategies today.[24] While major national research institutions argue that agricultural biotechnology is as safe as traditional crop varieties, environmental groups and a select group of scientists are concerned about the uncertainty associated with the use of new technologies. Furthermore, there are commercial entities that are concerned about the control of agricultural biotechnology supply by major corporations.[25]

Crop biotechnology was developed and had its first application in the mid-1990s. The technology identifies genes that perform specific functions and inserts them into crop varieties. Functions include resistance to certain pests, improvements in nutritional content, and tolerance to weather conditions. The development of a modified variety is subject to a large assortment of tests aimed at ensuring the variety performs well in the field without harm to humans or the environment. Once the molecular procedure of producing a new trait has been discovered, the trait can be inserted relatively easily into a large number of existing varieties of a given crop. The ability to introduce a trait to multiple varieties relatively cheaply is very useful in preserving crop biodiversity.[26]

Bennett suggests that there are hundreds of traits that are in various stages of development, so it is useful to distinguish between the three generations of traits.[27] First-generation traits are mostly related to pest-control. Second-generation traits aim to enhance quality, such as expanding shelf life, improving nutritional content by adding nutrients like vitamin A, increasing tolerance to changes in climate like droughts or floods, and enhancing digestibility by livestock. This is done in products like soybeans to reduce the amount of grain needed to feed livestock.

Third-generation traits may be used to replace products made from non-renewable resources, such as petroleum-based chemicals. First-generation varieties increase the supply of food. Second-generation traits increase both availability and quality of food, and thus increase food security.

Most of the existing large-scale applications of GE use first-generation traits in a select number of crops in only a few countries (e.g., the United States, India, and Brazil). This is primarily due to regulatory constraints and limited investment. In the United States, first-generation traits have been adopted in corn, soybean, cotton, rapeseed, and sugar beet, and several other applications are under regulatory review.[28] In India and China, first-generation traits are used mostly with cotton; China is considering other applications of GE, while in India there is strong political resistance to GE utilization expansion.[29] The EU has imposed a practical ban on the production of GE varieties—even though the EU consumes meats and oils that contain GE products—and many African countries share this perspective.[30] Much of the resistance towards GE is political in nature, and comes from interest groups, such as chemical companies and environmentalists opposed to the technology. However, despite the restriction of GE application to certain regions and crops, there is ample evidence documenting its widespread benefits.

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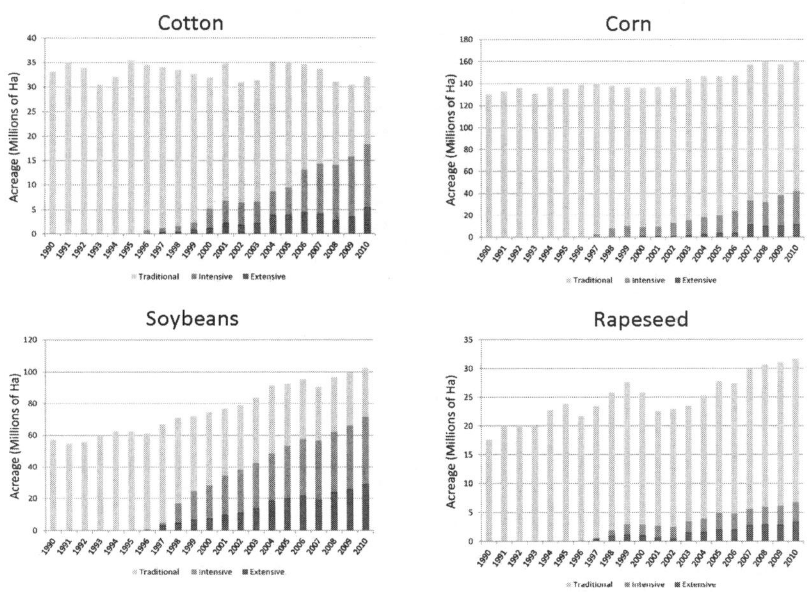
The growing contribution of GE varieties is apparent from their expansion. Figure 1 depicts the change in global acreage devoted to GE from 1990 to 2010 in four major crops. GE varieties both replace existing varieties as well as expand the area used to grow crops like corn and soybean.

As Figure 2 shows, more land is now allocated to GE crops in the developing world than the developed world, which is the result of the rapid expansion of GE corn and soybean in Brazil and Argentina, as well as GE cotton in China and India.[31] GE technology, however, has been minimally adopted in the production of corn and soybean in Africa (mostly in South Africa, Burkina Faso, and Egypt), and with the exception of papaya, it has not been adopted substantially in fruits and vegetables anywhere. This is despite evidence of a large number of GE varieties available for many of these crops. More importantly, there are significant potential benefits, as has been suggested by the adoption of insect resistant rice varieties in China.[32] The limited adoption in Africa was largely the result of political constraints and pressure from Europe, which, as we argue later, are very costly in both

Figure 1 depicts the evolution in the acreage devoted to the primary GE crops globally. It also indicates how much of this expansion takes place on the intensive margin (representing GE varieties replacing traditional varieties of a given crop) and extensive margin (representing the expansion of land allocated to grow a specific crop).[35]

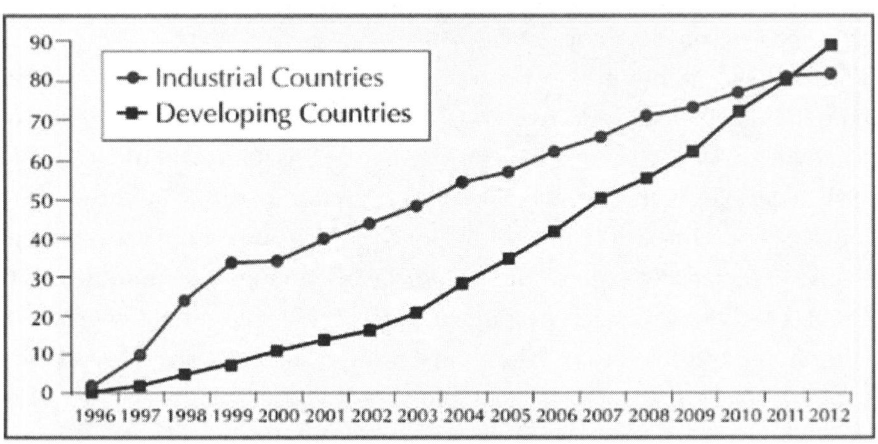
World area of four crops with genetically engineered varieties



Source: Barrows, Sexton, and Zilberman (2013).

Figure 2 shows the respective GE acreage in developed and developing countries.

Global area of biotech crops, 1996 to 2012: industrial and developing countries (million hectares)



Source: Clive James (2012).

economic and environmental terms.[33]

There is growing literature on the contribution of GE to agriculture and the environment.[34] Much of it assesses the economic impact of first-generation GE technologies. Studies have used the damage control framework that suggests the agricultural output is equal to potential output times one, minus the fraction of crop lost due to pest damage. Some inputs, like chemical pesticides or GE seeds, are called damage control inputs because they reduce pest damage.[36] This framework implies that GE is likely to increase yields in locations where it addresses pest problems that have not been controlled previously, or by reducing the use of alternative pest controls when it replaces an existing control.

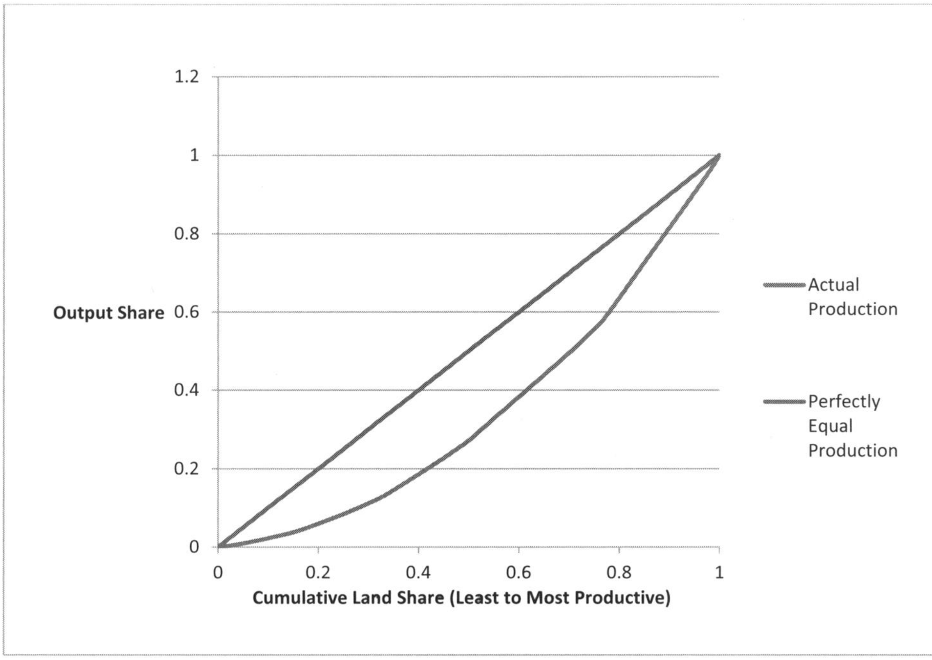
Genetically modified traits should be inserted into the best local varieties to augment them, rather than introduced by planting foreign, modified varieties.

GE technology has more potential to increase yield in tropical, developing countries, where pest problems are more severe and pesticide adoption is less common, than in developed countries in northern regions, where the weather is more moderate and alternative pesticides have already been adopted.[37] Genetically modified traits should be inserted into the best local varieties to augment them, rather than introduced by planting foreign, modified varieties. Some of the gains associated with the inserted trait may be lost by switching away from a local variety, which could also cause a loss of biodiversity.[38] While weather and land conditions explain many of the differences in crop yields between countries, much can be attributed to the lack of incentives for farmers—particularly in areas of significant untreated crop damage—to adopt fertilizer, invest in better seeds, or consider irrigation, even if these options are cheaply available. Case studies show that the adoption of GE has a significant effect on yields in regions in the developing world where pest damage is very high and where other pest controlling means are expensive or difficult to adopt.[39]

When the adoption of a trait tends to reduce pest damage significantly, it may lead to a "gene effect," an increased investment in complementary inputs like fertilizers and irrigation because of potentially compounded returns that could result in even greater yields.[40] This element of complementarity that increases productivity is quite important, as shown in Figure 3, which depicts the relationship between acreage and corn production globally. The least-productive 20 percent of land produces 5 percent of the total corn output, while the most-productive 5 percent produces about 20 percent of the total output. There is a yield ratio of 30:1 from the most-productive to least-productive corn producing countries. Adoption of

Figure 3

Distribution of corn output over land using a Lorenz curve



Source: Graph generated by authors using data from FAOSTAT (2013).

damage control varieties that reduce pest damage by 50 percent or more may lead to a virtuous cycle of adoption of complementary technologies.[41]

While early studies on the impact of GE varieties rely mostly on specific, regional case studies, more recent studies estimate the impact of GE adoption on global supply.[42] Analysis suggests that GE will be utilized in locations where pest damage problems are more substantial.[43] Thus, we do not expect global adoption of GE varieties and believe there are three types of regions considering adoption: regions with political constraints or insubstantial pest problems; regions where adoption is feasible and pest damage is significant enough to encourage the switch from the traditional varieties to modified ones (i.e., intensive margin effect); and regions where a specific crop was not grown because of severe pest damage, but can now produce the crop due to GE adoption (i.e., extensive margin effect).

Only 25 percent of corn grown globally uses GE technology, and most of this production takes place on the intensive margin, with only 5 percent of total acreage expanded due to the extensive margin effect.[44] Around 60 percent of the world cotton acreage in 2010 used GE technology, and most of the production took place on the intensive margin. The total acreage of cotton in the world has actually declined because of the significant yield effect of GE cotton, which led to increased supply and contained cotton prices.[45] In fact, some of the land used to grow cotton actually switched to growing corn, as the adoption rate of GE corn has been lower and the demand for corn has increased with the introduction of biofuel.[46]

Some early studies of GE technology's impact on yields suggest that it increased yields in cotton from 5 to 60 percent and in corn from 0 to 50 percent, while other studies suggest that comparing land grown with GE to land grown without it results in a global average yield effect 34, 12, and 3 percent for each of cotton, corn and soybean respectively. Of course, the variance in these estimates is significant. Using both estimates of the yield effect and extensive margin effect, in 2010 the supply of corn increased between 5 and 19 percent; the supply of cotton increased between 15 and 20 percent; and the supply of soybean increased between 2 and 40 percent. The differences in range depend on whether one takes into account the extensive margin. In the case of soybean, the lion's share of the yield effect is attributable to the extensive margin, while in corn and cotton it is mostly attributable to the intensive margin.[47]

This analysis suggests that more extensive adoption of GE corn could increase output enough to offset the amount converted to biofuel, especially in developing countries where the yield and complementarity effects may be much more substantial. It is plausible that soybean supply increased by around 30 percent because of GE, which has played a crucial role in growing demand for meat in China and other Asian countries like India and Indonesia, as soybeans are a primary source of feed grain for livestock. Actually, the increase in meat consumption in China over the last fifteen years is of the same order of magnitude as the increase in production of soybeans in Argentina, the latter of which became feasible through the introduction of GE.

The impact of GE varieties on supply is also reflected in the decline in food commodity prices. As we stated earlier, one measure of food security is the affordability of food and other agricultural products. The adoption of GE corn lowered international corn prices by 13 percent, cotton by 18 percent, and soybean between 2 and 65 percent.[48] These results suggest that GE technology has a significant impact on food security by increasing supply and reducing prices, even if its current adoption is restricted and limited. Clearly, there is potential for further improvement in food security, both in terms of the availability of food and in terms of price reductions, if GE adoption is expanded to countries in Africa and Europe and is introduced to other crops.

The Impact of GE Crops on Resources, Health, and the Environment

As a result of the supply-increasing effect of GE varieties, there have been reductions in the amount of land used to produce these crops.[49] Using the yield effect estimates of switching from non-GE to GE varieties, it is estimated that farmers can reallocate about 20 percent of land used to produce cotton without reducing supply, and 8 percent for corn.[50] The ability to move to double-cropping in soybeans has also reduced the footprint of agriculture substantially.[51] The increase in the number of traits (e.g. herbicide-tolerant, drought-tolerant, etc.) adopted will increase the yield and water-saving effects. Additionally, the adoption of GE technology in crops such as rice and wheat would help to reduce the footprint of agriculture and allow for the production of more output on existing land.

Another major advantage of GE technologies is that they provide new avenues to adapt to changes in climatic conditions, such as increased drought.

Another major advantage of GE technologies is that they provide new avenues to adapt to changes in climatic conditions, such as increased drought. As concerns about climate change increase, the value of these technologies will become more prominent.[52] The yield effect and other efficiency-enhancing effects associated with the adoption of GE varieties will not only save land, but also water and energy used in agricultural production. They will also substantially reduce the greenhouse gas (GHG) effect of agriculture.[53] The adoption of herbicide-tolerant varieties has already enabled extensive adoption of low- and no-tillage technologies, which has led to a sizeable reduction in the GHG emission impact on agriculture.

As argued earlier, food security is measured not only by the availability of food, but also in the enhancement of nutritional value, which is especially appropriate in the context of developing countries, where limited access to crucial vitamins and minerals leads to poor diets. Studies have shown that only 25 percent of GE varieties in field trials target pest control or are third-generation traits that attempt to enhance the nutritional value of food.[54] The potential of this research to improve human well-being is vast. For example, vitamin A deficiency is a major cause of blindness among children in Asia and Africa. Golden Rice is a GE variety of rice that has increased vitamin A content and has been available for commercialization since 2002, but regulatory pressure has prevented its introduction. Studies have estimated that earlier introduction of Golden Rice could have reduced vitamin A deficiency in children in Asia and Africa and prevented 600,000 to 1.2 million cases of blindness.[55]

While the adoption of GE crops is likely to improve food quality, and thus improve health, there have been concerns regarding some of its negative effects. Indeed, the introduction of new traits should be accompanied by regulatory procedures that assure that the new traits do not negatively affect human health and the environment; this is the role of biosafety regulations.[56] Paarlberg has found evidence from the British Medical Association, Académie des Sciences, Organisation for Economic Cooperation and Development, and the Food and Agricultural Organization of the United Nations that to date, crops and foods that are labeled genetically modified organisms (GMO) have not resulted in human or environmental health risks.[57] Moreover, the adoption of GE technologies has manifested certain health benefits: the reduction of risk from mycotoxin accumulation in food in developing countries and the reduction of incidents of pesticide-related health problems globally, for instance.[58]

One major challenge associated with the adoption of GE is the emergence of pests resistant to the gene modification.[59] This can be controlled through management practices, including the use of refugia where part of the land is allocated to non-GE varieties. Still, evolutionary forces may lead to the emergence of resistance, suggesting the need for continuous improvement in crop management strategies. This is another reason why ongoing investment in research to develop and improve agricultural biotechnologies in response to evolving realities should continue. In particular, funding should be allocated for public sector research to address emerging pest problems.

Policy Reforms to Improve GE Utilization in the Future

Our analysis suggests that agricultural biotechnology has already made an important contribution to food security by increasing supply, reducing prices, and reducing the footprint and resource requirements of agriculture. But GE is in its infancy—it has only been applied in the last 30 years—and the knowledge base for expansion of the technology still needs to be developed. Two major constraints limit the technology from reaching its potential. The first is related to intellectual property considerations. Given that the private sector developed many of the basic GE innovations, private companies hold the rights to develop these patents and are the most likely to pursue further development of these technologies. Private companies may not take into account the benefit their products provide to consumers beyond price, so they may—from a societal perspective—be inclined to underinvest. For example, they may not develop biotechnology products that have additional benefit for the poor, or may underinvest in specialty crops with relatively small market sizes, like papaya and carrots.[60] Introducing mechanisms like a clearinghouse for agricultural biotechnology property rights will improve access to GE technology for specialty crops and crops in developing countries, which may assist in curtailing these impacts.[61]

A second constraint is regulation. In most of Europe and many other countries, the production of GE crops is essentially banned.[62] The introduction of this ban in

Europe around 1998 was associated with the constriction of agricultural biotechnology research within other countries.[63] The practical ban on biotechnology in many parts of the developing world and its limited use in countries like China and India increases the price of food, and as a consequence, hurts the poor.[64] In other countries, including the United States, the cost of introducing new GE technology is very high and the regulatory process uncertain.[65] This reduces the incentives to invest, develop, and introduce these technologies. Thus, it is important to introduce rational regulatory procedures that continue to screen against possible risk, while at the same time reducing the cost and uncertainty of regulatory outcomes. This regulatory process would be precise and aim to reduce redundancy, which is likely to induce significant development and adoption of GE innovations.[66]

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Conclusion

While the adoption and utilization of agricultural biotechnology has provided much of the increases in the supply of important grain crops, most agricultural products, including fruits and vegetables, have not benefitted from this technology. This is often due to regulation, insufficient investment in research and development, or a combination of the two. As we have argued, addressing the food security challenges associated with population growth, climate change, and increases in income require society to take advantage of technologies that increase the productivity and reduce the environmental footprint of agriculture. GE technologies fit this profile. They take advantage of modern developments in molecular and cellular biology that revolutionized the medical sector, and it is time to allow them to make a similar impact in agriculture.

Additionally, in order to expand the uses of agricultural biotechnology, the public has to become aware of the benefits and costs associated with its underutilization. The public needs to be assured that the technology is safe. An effective regulatory structure, especially in Europe, Asia, and Africa, can help accomplish this. Of course, regulation should not be onerous or redundant, and should allow the viable GE sector to flourish and contribute to food security and sustainable development, while at the same time ensuring public safety.

In spite of its limited application, agricultural biotechnology has increased food supply, reduced food costs, and increased farmer safety. Through continuing investment in these technologies and reforming regulation to allow it to meet its potential, GE can increase the availability and affordability of food, improve environmental quality, and enable more effective adaptation to climate change.

NOTES

1 Kees Klein Goldewijk, "Estimating Global Land Use Change over the Past 300 years: The HYDE Database," *Global Biogeochemical Cycles* 15, no. 2 (June 2001), 417-433.

2 David Tilman et al., "Global Food Demand and the Sustainable Intensification of Agriculture," *Proceedings of the National Academy of Sciences* 108, no. 50 (December 2011), 20260-20264.

3 H. Charles J. Godfray et al., "Food Security: The Challenge of Feeding 9 Billion People," *Science* 327, no. 5967 (February 2010), 812-818.

4 Wolfram Schlenker and Michael J. Roberts, "Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change," *Proceedings of the National Academy of Sciences* 106, no. 37 (September 2009), 15594-15598.

5 Steven Sexton is an assistant professor of agricultural economics at North Carolina State University, specializing in environmental economics. Geoffrey Barrows is a PhD student in the Department of Agricultural and Resource Economics at the University of California, Berkeley, specializing in environmental and trade economics.

6 Per Pinstrup-Andersen, Rajul Pandya-Lorch, and Mark W. Rosegrant, "World Food Prospects: Critical Issues for the Early Twenty-First Century," (Global Food Policy Report, International Food Policy Research Institute, Washington DC: 1999).

7 David Zilberman et al., "Technology and the Future Bioeconomy," *Agricultural Economics* 44, no. 1 (November 2013), 95-102.

8 Ibid.

9 Hartwig De Haen et al., "The World Food Economy in the Twenty-first Century: Challenges for International Co-operation," *Development Policy Review* 21, no. 5-6 (September 2003), 683-696.

10 Prabhu Pingali, Luca Alinovi, and Jacky Sutton, "Food Security in Complex Emergencies: Enhancing Food System Resilience," *Disasters* 29, no. 1 (June 2005), S5-S24.

11 Thomas Jayne, Ballard Zulu, and J. J. Nijhoff, "Stabilizing Food Markets in Eastern and Southern Africa," *Food Policy* 31, no. 4 (2006), 328-341.

12 Pingali, Alinovi, and Sutton, S5-S24.

13 Ganesh Kishore and Christine Shewmaker, "Biotechnology: Enhancing Human Nutrition in Developing and Developed Worlds," *Proceedings of the National Academy of Sciences* 96, no. 11 (May 1999), 5968-5972.

14 Clive James, "Global Status of Commercialized Biotech/GM Crops," (Brief no. 41, International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY: 2009), 182.

15 Jared Diamond, *Guns, Germs and Steel: The Fate of Human Societies* (New York: W.W. Norton and Company, 1997).

16 According to the World Commission on Environment and Development (WCED), sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." See United Nations, *"Our Common Future: Report of the World Commission on Environment and Development"* (document transmitted to the General Assembly, United Nations, New York: 1987).

17 David Zilberman, "The Economics of Sustainable Development," *American Journal of Agricultural Economics* (September 24, 2013), http://ajae.oxfordjournals.org/content/early/2013/09/24/ajae.aat075.full.

18 David Zilberman, Jinhua Zhao, and Amir Heiman, "Adoption versus Adaptation, with Emphasis

on Climate Change," *Annual Review of Resource Economics* 4, no. 1 (August 2012), 27-53.

19 David Zilberman et al., "The Economics of Climate Change In Agriculture," *Mitigation and Adaptation Strategies for Global Change* 9, no. 4 (2004), 365-382.

20 Ibid.

21 Zilberman, Zhao, and Heiman.

22 Michael Edgerton, "Increasing Crop Productivity to Meet Global Needs for Feed, Food, and Fuel," *Plant Physiology* 149, no. 1 (January 2009), 7-13.

23 Alan B. Bennett et al., "Agricultural Biotechnology: Economics, Environment, Ethics, and the Future," *Annual Review of Environment and Resources* 38, no. 1 (October 2013), 249-279.

24 We will not address animal cloning, which is another important and controversial biotechnology.

25 David Zilberman et al., "Continents Divided: Understanding Differences between Europe and North America in Acceptance of GM Crops." *GM Crops and Food: Biotechnology in Agriculture and the Food Chain* 4, no. 3 (2013), 202-208.

26 David Zilberman, Holly Ameden, and Matin Qaim, "The Impact of Agricultural Biotechnology on Yields, Risks, and Biodiversity in Low-Income Countries," *The Journal of Development Studies* 43, no. 1 (2007), 63-78.

27 Bennett et al. (2013).

28 Bennett et al. (2013).

29 Clive James, "Global Status of Commercialized Biotech/GM Crops," (Brief no. 44, International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY: 2012).

30 Robert Paarlberg, *Starved For Science: How Biotechnology is Being Kept Out of Africa*. (Cambridge: Harvard University Press, 2009).

31 Eduardo Trigo and Eugenio Cap, "The Impact of the Introduction of Transgenic Crops in Argentinean Agriculture," *AgBioForum* 6, no. 3 (2003), 87-94. James (2012).

32 Bennett et al. (2013); Jikun Huang et al., "Insect-Resistant GM Rice in Farmers' Fields: Assessing Productivity and Health Effects in China," *Science* 308, no. 5722 (April 2005), 688-690.

33 Paalberg (2009).

34 Matin Qaim, "The Economics of Genetically Modified Crops," *Annual Review of Resource Economics* 1 (June 2009), 665-694; National Research Council Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability, "Impact of Genetically Engineered Crops on Farm Sustainability in the United States" (brief, The National Academies Press, Washington, DC: 2012); Bennett et al. (2013); Barrows, Sexton, and Zilberman (Winter 2014).

35 Geoffrey Barrows, Steven Sexton, and David Zilberman, "Agriciltural Biotechnology: The Promise and Prospects of Genetically Modified Crops," *Journal of Economic Perspectives* 28, no. 1 (Winter 2014), 99-120.

36 Erik Lichtenberg and David Zilberman, "The Econometrics of Damage Control: Why Specification Matters," *American Journal of Agricultural Economics* 68, no. 2 (May 1986), 261-273.

37 Matin Qaim and David Zilberman, "Yield Effects of Genetically Modified Crops in Developing Countries," *Science* 299, no. 5608 (2003), 900-902.

38 Ibid.

39 Ibid.

40 Qaim (2009); José Falck-Zepeda, Guillaume P. Gruère, and Idah Sithole-Niang, eds., *Genetically Modified Crops in Africa: Economic and Policy Lessons from Countries South of the Sahara* (Washington DC: International Food Policy Research Institute, 2013).

41 Barrows, Sexton, and Zilberman (Winter 2014).

42 Barrows, Sexton, and Zilberman (Winter 2014); Geoffrey Barrows, Steven Sexton, and David Zilberman, "The Impact of Agricultural Biotechnology on Supply and Land Use" (working paper, CUDARE Working Papers Series 1133, University of California at Berkeley, Berkeley: 2013).

43 Paul A. David, *A Contribution to the Theory of Diffusion* (Palo Alto: Research Center in Economic Growth, Stanford University, 1969); Gershon Feder, Richard E. Just, and David Zilberman, "Adoption of Agricultural Innovations in Developing Countries: A Survey," *Economic Development and Cultural Change* 33, no. 2 (1985), 255-298.

44 Barrows, Sexton, and Zilberman (Winter 2014).

45 James (2012).

46 Barrows, Sexton, and Zilberman (Winter 2014).

47 Ibid.

48 Ibid.

49 Qaim (2009); National Research Council (2012); Bennett et al. (2013).

50 Barrows, Sexton, and Zilberman (2013).

51 James Cook, "Toward Cropping Systems that Enhance Productivity and Sustainability," *Proceedings of the National Academy of Sciences* 103, no. 49 (2006), 18389-18394.

52 Bennett et al. (2013).

53 Barrows, Sexton, and Zilberman (2013).

54 Bennett et al. (2013).

55 Justus Wesseler and David Zilberman, "The Economic Power of the Golden Rice Opposition," *Environment and Development Economics* (January 2014), http://dx.doi.org/10.1017/S1355770X1300065X; Justus Wesseler, Scott Kaplan, and David Zilberman, "The Cost of Delaying Approval of Golden Rice," *Agricultural and Resource Economics* (forthcoming).

56 Gregory Jaffe, "Straight Talk on Genetically Engineered Foods: Answers to Frequently Asked Questions," (report, Center for Science in the Public Interest, Washington DC: 2012).

57 Robert Paarlberg, "GMO Foods and Crops: Africa's Choice," *New Biotechnology* 27, no. 5 (November 2010), 609-613.

58 Felicia Wu, "Mycotoxin Reduction in Bt Corn: Potential Economic, Health, and Regulatory Impacts," *Transgenic Research* 15, no. 3 (September 2006), 277-289; Bennett et al. (2013).

59 Barrows, Sexton, and Zilberman (Winter 2014).

60 Zilberman et al. (2013), 202-208.

61 Gregory D. Graff et al., "The Public-Private Structure of Intellectual Property Ownership in Agricultural Biotechnology," *Nature Biotechnology* 21, no. 9 (September 2003), 989-995.

62 Koreen Ramessar et al., "Going to Ridiculous Lengths—European Coexistence Regulations for GM Crops," *Nature Biotechnology* 28, no. 2 (2010), 133.

63 Gregory Graff, David Zilberman, and Alan Bennett, "The Contraction of Agbiotech Product Quality Innovation," *Nature Biotechnology* 27, no. 8 (2009), 702-704.

64 Barrows, Sexton, and Zilberman (Winter 2014).

65 Nicholas Kalaitzandonakes, Julian M. Alston, and Kent J. Bradford, "Compliance Costs for Regulatory Approval of New Biotech Crops," *Nature Biotechnology* 25, no. 5 (2007), 509-511.

66 David Zilberman, "The Economics of Biotechnology Regulation," in *Regulating Agricultural Biotechnology: Economics and Policy*, ed. Richard Just, Julian Alston, and David Zilberman (New York: Springer, 2006), 243-261.