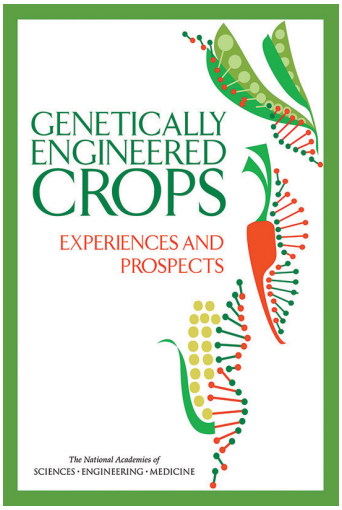
REPORT IN BRIEF
May 2016
Board on Agriculture and Natural Resources
DIVISION ON EARTH AND LIFE STUDIES

Genetically Engineered Crops: Experiences and Prospects



New technologies in genetic engineering and conventional breeding are blurring the once clear distinctions between these two crop-improvement approaches. While recognizing the inherent difficulty of detecting subtle or long-term effects in health or the environment, the study committee found no substantiated evidence of a difference in risks to human health between currently commercialized genetically engineered (GE) crops and conventionally bred crops, nor did it find conclusive cause-and-effect evidence of environmental problems from the GE crops. GE crops have generally had favorable economic outcomes for producers in early years of adoption, but enduring and widespread gains will depend on institutional support and access to profitable local and global markets, especially for resource-poor farmers.

Claims and research that extol both the benefits of and risks posed by GE crops and food have created a confusing landscape for the public and policy-makers. Using evidence accumulated over the last two decades, this report assesses purported negative effects and purported benefits of currently commercialized GE crops. The report also assesses emerging genetic-engineering technologies, how they might contribute to future crop improvement, and what technical and regulatory challenges they may present. To carry out its task, the report's authoring committee delved into the relevant literature (more than 900 research and other publications), heard from 80 diverse speakers at three public meetings and 15 webinars, and read more than 700 comments from members of the public to broaden its understanding of issues surrounding GE crops.

EXPERIENCES WITH GENETICALLY ENGINEERED CROPS

Since the 1980s, biologists have used genetic engineering in crop plants to alter characteristics, such as longer shelf life for fruit, higher vitamin content, and resistance to diseases. However, the only characteristics that have been introduced through genetic engineering into widespread commercial use are those that provide insect resistance and herbicide resistance. In 2015, GE herbicide resistance, insect resistance, or both were available in fewer than 10 crop species and grown on about 12 percent of the world's planted cropland (see Figure 1). In its evaluation of experiences with GE crops, the committee examined the long-term data available on the use of insect and herbicide resistance in the most commonly grown GE crops to date: soybean, cotton, and maize. A few other GE characteristics—such as for resistance to specific viruses in papaya and squash and reduction of browning in the flesh of apples and potatoes—have been incorporated into some crops in commercial production as of 2015, but were produced on a relatively small number of hectares worldwide.

Agronomic and Environmental Effects

Insect-resistant GE crops contain genes from *Bacillus thuringiensis (Bt)*, a soil bacterium that gives crops a built-in insecticide. Plants with this characteristic can kill targeted

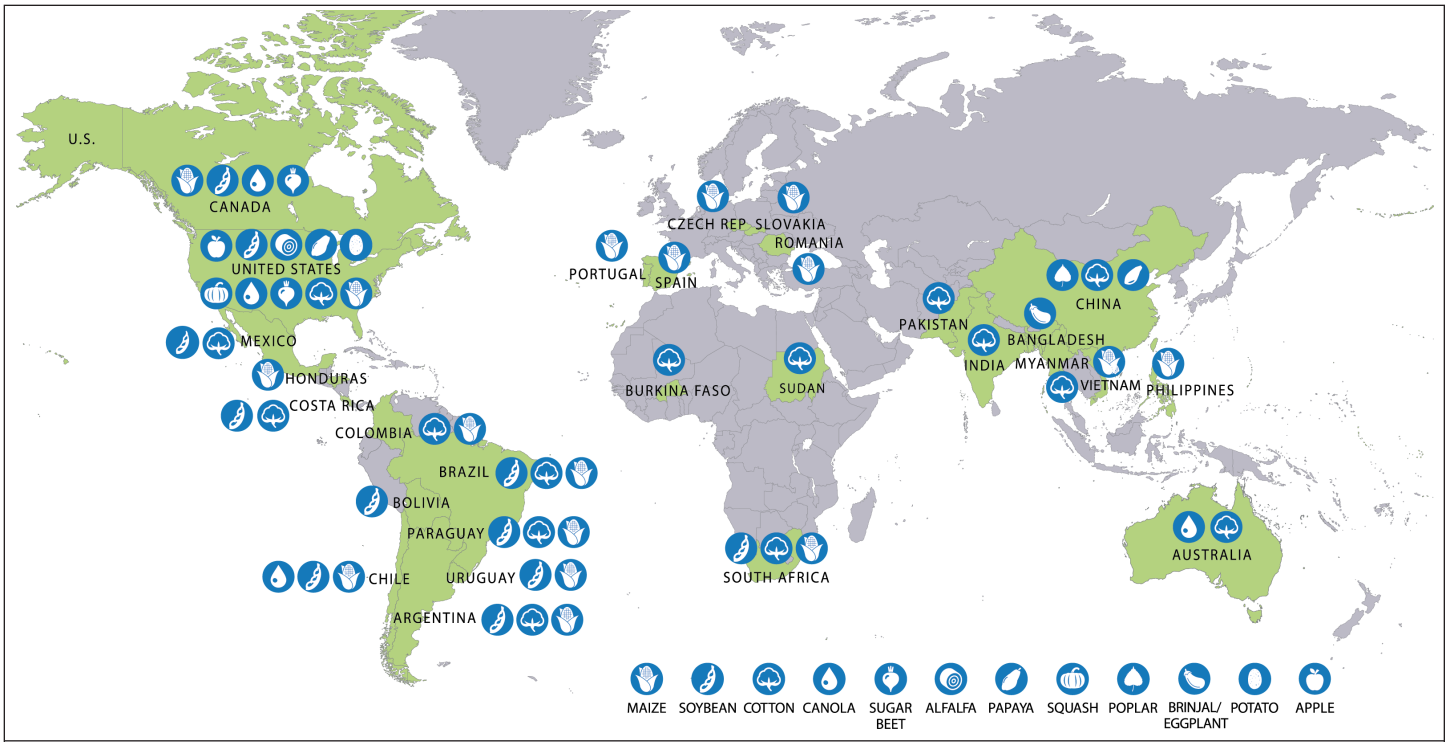


FIGURE 1. Commercially Grown GE Crops Worldwide. *In 2015, almost 180 million hectares of GE crops were planted globally, which was about 12 percent of the world's planted cropland that year. There were herbicide-resistant varieties of maize, soybean, cotton, canola, sugar beet, and alfalfa, and insect-resistant varieties of maize, cotton, poplar, and eggplant.*

insects that ingest them. Following are conclusions about various effects of *Bt* crops based on available data:

- ***Bt* Crop Yield.** *Bt* in maize and cotton from 1996 to 2015 contributed to a reduction in crop losses (closing the gap between actual yield and potential yield) under circumstances where targeted insect pests caused substantial damage to non-*Bt* varieties and synthetic chemicals could not provide practical control.
- **Abundance and diversity of insects.** In areas of the United States and China where adoption of either *Bt* maize or *Bt* cotton is high, some insect-pest populations are reduced regionally, benefiting both adopters and nonadopters of *Bt* crops. Some secondary (nontargeted) insect pests have increased in abundance, but there are only a few cases where the increase has posed an agronomic problem. Planting *Bt* crops tended to result in higher insect biodiversity than planting similar varieties without the *Bt* trait and using synthetic insecticides.
- **Insecticide use.** Application of synthetic insecticides to maize and cotton has decreased following the switch from non-*Bt* varieties to *Bt* varieties, and in some cases, the use of *Bt* crops has been associated with lower use of insecticides in non-*Bt* varieties of the crop and other crops in the same area.
- **Insect resistance.** Target insects have been slow to evolve resistance to *Bt* proteins when crops produced a high enough dose of *Bt* protein to kill insects with partial genetic resistance to the toxin and there were refuges where susceptible insects survived. Where resistance-management strategies were not followed, damaging levels of resistance evolved in some target insects.

Herbicide resistance allows a crop to survive the application of a herbicide which would otherwise kill it. Most herbicide-resistant GE crops are engineered to be resistant to glyphosate, commonly known as RoundUp®. Conclusions based on the available evidence include the following:

- **Herbicide-resistant crop yield.** Studies indicate that herbicide-resistant crops contribute to greater yield where weed control is improved because of the specific herbicides that can be used in conjunction with the herbicide-resistant crop.
- **Herbicide use.** Total kilograms of all types of herbicide applied per hectare of crop per year declined when herbicide-resistant crops were first adopted, but the decreases have not generally been sustained. However, total kilograms of herbicide applied per hectare is an uninformative metric for assessing changes in risks to the environment or to human health due to GE crops; because the environmental and health hazards of different herbicides vary, the relationship of kilograms of herbicide applied per hectare and risk is poor.
- **Weed-species distribution.** In locations where glyphosate is used extensively, weed species that are naturally less susceptible to that herbicide may populate a field. The committee found little evidence that agronomic harm had resulted from such shifts in weed species.
- **Weed resistance.** In many locations, some weeds have evolved resistance to glyphosate. Integrated weed-management approaches can be used to delay resistance, especially in cropping systems not yet exposed to continuous glyphosate applications. Further

research is needed to improve strategies for management of resistance in weeds.

Overall, the committee found no conclusive evidence of cause-and-effect relationships between GE crops and environmental problems. However, the complex nature of assessing long-term environmental changes often made it difficult to reach definitive conclusions.

Comparisons with conventional breeding

The committee assessed detailed surveys and experiments comparing GE to non-GE crop yields and also examined changes over time in overall yield per hectare of maize, soybean, and cotton reported by the U.S. Department of Agriculture (USDA) before, during, and after the switch from conventionally bred to GE varieties of these crops. Although the sum of experimental evidence indicates that GE herbicide resistance and insect resistance are contributing to actual yield increases, there is no evidence from USDA data that the average historical rate of increase in U.S. yields of cotton, maize, and soybean has changed.

Human Health Effects

GE crops and foods derived from them are tested in three ways: animal testing, compositional analysis, and allergenicity testing and prediction. Although the design and analysis of many animal-feeding studies were not optimal, the many available animal experimental studies taken together provided reasonable evidence that animals were not harmed by eating foods derived from GE crops. Data on the nutrient and chemical composition of a GE plant compared to a similar non-GE variety of the crop sometimes show statistically significant differences in nutrient and chemical composition, but the differences have been considered to fall within the range of naturally occurring variation found in currently available non-GE crops.

Many people are concerned that GE food consumption may lead to higher incidence of specific health problems including cancer, obesity, gastrointestinal tract illnesses, kidney disease, and disorders such as autism spectrum and allergies. In the absence of long-term, case-controlled studies to examine some hypotheses, the committee examined epidemiological datasets over time from the United States and Canada, where GE food has been consumed since the late 1990s, and similar datasets from the United Kingdom and western Europe, where GE food is not widely consumed. No pattern of differences was found among countries in specific health problems after the introduction of GE foods in the 1990s.

Social and Economic Effects

At the farm level, soybean, cotton, and maize with GE herbicide-resistant or insect-resistant traits (or both) have generally had favorable economic outcomes for producers who have adopted these crops, but there is high heterogeneity in outcomes. The utility of a GE variety to a specific farm system depends on the fit of the GE characteristic and the genetics of the variety to the farm environment and the quality and cost of the GE seeds. In some situations in which farmers have adopted GE crops without identifiable economic benefits, increases in management flexibility and other considerations may be driving adoption of GE crops, especially those with herbicide resistance.

The cost of GE seed may limit the adoption of GE crops by resource-poor smallholders. In most situations, the differential cost between GE and non-GE seed is a small fraction of total costs of production, although it may constitute a financial constraint because of limited access to credit. In addition, small-scale farmers may face a financial risk when purchasing a GE seed upfront if the crop fails.

The committee heard diverse opinions on the ability of GE crops to affect food security in the future. GE crops, like other technological advances in agriculture, are not able by themselves to address fully the wide variety of complex challenges that face smallholders. Such issues as soil fertility, integrated pest management, market development, storage, and extension services all need to be addressed to improve crop productivity, decrease post-harvest losses, and increase food security. Even if a GE crop may improve productivity or nutritional quality, its ability to benefit intended stakeholders will depend on the social and economic contexts in which the technology is developed and diffused.

PROSPECTS FOR GENETIC ENGINEERING OF CROPS

Emerging genetic-engineering technologies such as CRISPR/Cas9 promise to increase the precision with which changes can be made to plant genomes and expand the array of characteristics that can be changed or introduced, such as: improved tolerance to drought and thermal extremes; increased efficiency in photosynthesis and nitrogen use; and improved nutrient content. Insect and disease resistance are likely to be introduced into more crop species and the number of pests targeted will also likely increase. If deployed appropriately, such characteristics will almost certainly increase harvestable yields and decrease the probability of crop losses to major insect or disease outbreaks. However, it is too early to know whether complex genetic changes that substantially improve photosynthesis, increase nutrient-use efficiency, and increase maximum yield will be successfully deployed. Therefore, the committee recommends balanced public investment in emerging genetic-engineering technologies and other approaches to address food security.

REGULATION SHOULD FOCUS ON NOVEL CHARACTERISTICS AND HAZARDS

All technologies for improving plant genetics—whether GE or conventional—can change foods in ways that could raise safety issues. Therefore, it is the product that should be regulated, the report finds, not the process (i.e., genetic-engineering or conventional-breeding techniques). New plant varieties should undergo safety testing if they have intended or unintended novel characteristics with potential hazards.

The United States' current policy on new plant varieties is in theory a product-based policy, but USDA and the Environmental Protection Agency (EPA) determine which plants to regulate at least partially on the process by which they are developed. This approach is becoming less technically defensible as emerging technologies blur

the distinctions between genetic engineering and conventional plant breeding. For example, CRISPR/Cas9 could make a directed change in the DNA of a crop plant that leads to increased resistance to an herbicide; the same change could be made using chemical- or radiation-induced mutagenesis in thousands of individual plants followed by genome screening to isolate plants with the desired mutation—an approach considered conventional breeding by most national regulatory systems

The report recommends the development of a tiered approach to safety testing using as criteria novelty (intended and unintended), potential hazard, and exposure. New -omics technologies—such as proteomics and transcriptomics—that can compare the DNA sequence, RNA expression, and molecular composition of a new variety with counterparts already in widespread use will allow such testing for novel characteristics, better enabling the tiered approach (see Figure 2). The committee is aware that -omics technologies are new and that not all developers of crop varieties will have access to them; therefore, public investment will be needed.

Regulating authorities should be proactive in communicating information to the public about how emerging genetic-engineering technologies or their products might be regulated and how new regulatory methods may be used. They should also proactively seek input from the public on these issues. Policy regarding GE crops has scientific, legal, and social dimensions, and not all issues can be answered by science alone, the report finds.

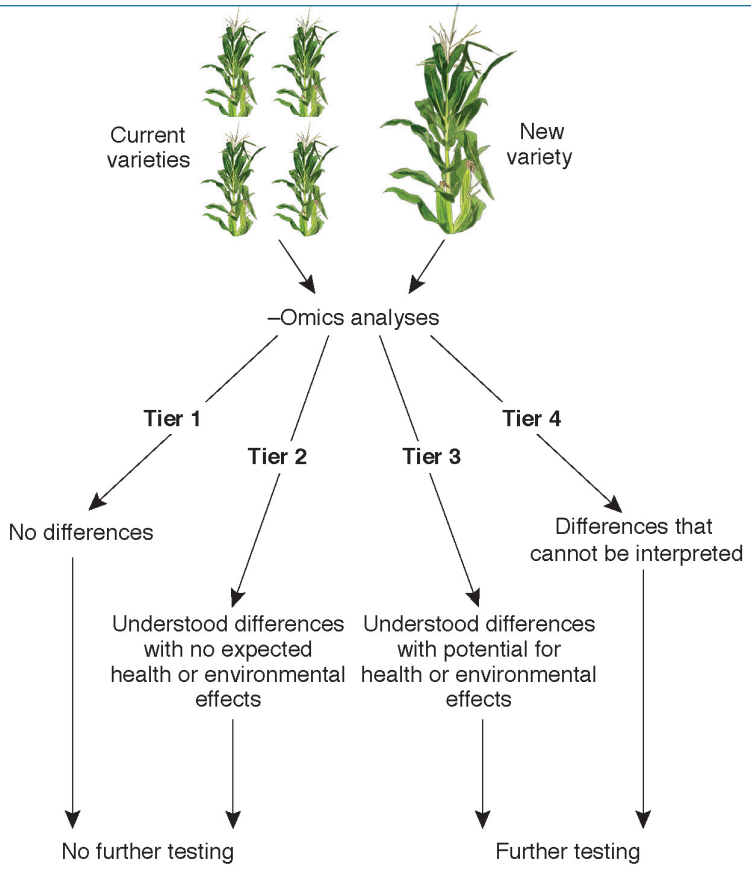


FIGURE 2. Proposed Strategy for Evaluating Crops Using -Omics Technologies. *New -omics technologies could be used to determine the extent to which the novel characteristics of the plant variety are likely to pose a risk to human health or the environment, regardless of whether the plant was developed using genetic-engineering or conventional-breeding processes.*

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The National Academies of Sciences, Engineering, and Medicine appointed the above committee of experts to address the specific task requested by the Burroughs Wellcome Fund, Gordon and Betty Moore Foundation, New Venture Fund, U.S. Department of Agriculture, and National Academy of Sciences. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the Academies. This report brief was prepared by the Academies based on the committee's report.

For more information, contact the Board on Agriculture and Natural Resources at (202) 334-3062 or visit at **http://nas-sites.org/ge-crops**. Copies of *Genetically Engineered Crops: Experiences and Prospects* are available from the National Academies Press, 500 Fifth Street, NW, Washington, DC 20001; (800) 624-6242; or as free PDFs at **www.nap.edu**.