Summary

With the advent of genetic-engineering technology in agriculture, the science of crop improvement has evolved into a new realm. Advances in molecular and cellular biology now allow scientists to introduce desirable traits from other species into crop plants. The ability to transfer genes between species is a leap beyond crop improvement through previous plant-breeding techniques, whereby desired traits could be transferred only between related types of plants. The most commonly introduced genetically engineered (GE) traits allow plants either to produce their own insecticide, so that the yield lost to insect feeding is reduced, or to resist herbicides, so that herbicides can be used to kill a broad spectrum of weeds without harming crops. Those traits have been incorporated into most varieties of soybean, corn, and cotton grown in the United States.

Since their introduction in 1996, the use of GE crops in the United States has grown rapidly and accounted for over 80 percent of soybean, corn, and cotton acreage in the United States in 2009. Several National Research Council reports have addressed the effects of GE crops on the environment and on human health. However, the effects of agricultural biotechnology at the farm level—that is, from the point of view of

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the farmer—have received much less attention. To fill that information gap, the National Research Council initiated a study, supported by its own funds, of how GE crops have affected U.S. farmers—their incomes, agronomic practices, production decisions, environmental resources, and personal well-being. This report of the study’s findings expands the perspectives from which genetic-engineering technology has been examined previously. It provides the first comprehensive assessment of the effects of GE-crop adoption on farm sustainability in the United States (Box S-1).

In interpreting its task, the committee chose to analyze the effects of GE crops on farm-level sustainability in terms of environmental, economic, and social effects. To capture the broad array of potential effects, the committee interpreted “farm level” as applying both to farmers who do not produce GE crops and those who do because genetic engineering is a technology of extensive scope, and its influences on farming practices have affected both types of farmers. Therefore, to the extent that peer-reviewed literature is available, the report draws conclusions about the environmental, economic, and social effects, both favorable and unfavorable, associated with the use of GE crops for all farmers in the United States over the last 14 years. The report encapsulates what is known about the effects of GE crops on farm sustainability and identifies where more

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**BOX S-1**

**Statement of Task**

An NRC committee will study the farm-level impacts of biotechnology, including the economics of adopting genetically engineered crops, changes in producer decision making and agronomic practices, and farm sustainability.

The study will:

- review and analyze the published literature on the impact of GE crops on the productivity and economics of farms in the United States;
- examine evidence for changes in agronomic practices and inputs, such as pesticide and herbicide use and soil and water management regimes;
- evaluate producer decision making with regard to the adoption of GE crops.

In a consensus report, the committee will present the findings of its study and identify future applications of plant and animal biotechnology that are likely to affect agricultural producers’ decision making in the future.
research is needed. A full sustainability assessment of GE crops remains an ongoing task because of information gaps on certain environmental, economic, and social impacts.

Genetic-engineering technology continues to stir controversy around scientific issues and ideological viewpoints. This report addresses just the scientific questions and adopts an “evidentiary” standard of using peer-reviewed literature to form conclusions and recommendations. GE-trait developments may or may not turn out to be a cost-effective approach to addressing challenges confronting agriculture, but a review of their impact and an exploration of what is possible are necessary to evaluate their relative efficacy. Therefore, the report details the challenges and opportunities for future GE crops and offers recommendations on how crop-management practices and future research and development efforts can help to realize the full potential offered by genetic engineering.

KEY FINDINGS

The order of findings in this summary reflects the structure of the report and does not connote any conclusions on the part of the committee regarding the relative strength or importance of the findings. In general, the committee finds that genetic-engineering technology has produced substantial net environmental and economic benefits to U.S. farmers compared with non-GE crops in conventional agriculture. However, the benefits have not been universal; some may decline over time; and the potential benefits and risks associated with the future development of the technology are likely to become more numerous as it is applied to a greater variety of crops. The social effects of agricultural biotechnology have largely been unexplored, in part because of an absence of support for research on them.

Environmental Effects

Generally, GE crops have had fewer adverse effects on the environment than non-GE crops produced conventionally. The use of pesticides with toxicity to nontarget organisms or with greater persistence in soil and waterways has typically been lower in GE fields than in non-GE, nonorganic fields. However, farmer practices may be reducing the utility of some GE traits as pest-management tools and increasing the likelihood of a return to more environmentally damaging practices.

Finding 1. When adopting GE herbicide-resistant (HR) crops, farmers mainly substituted the herbicide glyphosate for more toxic herbicides.
However, the predominant reliance on glyphosate is now reducing the effectiveness of this weed-management tool.

Glyphosate kills most plants without substantial adverse effects on animals or on soil and water quality, unlike other classes of herbicides. It is also the herbicide to which most HR crops are resistant. After the commercialization of HR crops, farmers replaced many other herbicides with glyphosate applications after crops emerged from the soil (Figures S-1, S-2, and S-3). However, the increased reliance on glyphosate after the widespread adoption of HR crops is reducing its effectiveness in some situations. Glyphosate-resistant weeds have evolved where repeated applications of glyphosate have constituted the only weed-management tactic. Ten weed species in the United States have evolved resistance to glyphosate since the introduction of HR crops in 1996 compared with seven that have evolved resistance to glyphosate worldwide in areas not growing GE crops since the herbicide was commercialized in 1974. Furthermore, communities of weeds less susceptible to glyphosate are

![Graph showing the application of herbicide to soybean and percentage of acres of herbicide-resistant soybean.](image)

**FIGURE S-1** Application of herbicide to soybean and percentage of acres of herbicide-resistant soybean.

NOTE: The strong correlation between the rising percentage of HR soybean acres planted over time, the increased applications of glyphosate, and the decreased use of other herbicides suggests but does not confirm causation between these variables.

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FIGURE S-2 Application of herbicide to cotton and percentage of acres of herbicide-resistant cotton.

NOTE: The strong correlation between the rising percentage of HR cotton acres planted over time, the increased applications of glyphosate, and the decreased use of other herbicides suggests but does not confirm causation between these variables.


becoming established in fields planted with HR crops, particularly fields that are treated only with glyphosate.

Finding 2. The adoption of HR crops complements conservation tillage practices, which reduce the adverse effects of tillage on soil and water quality.

Farmers have traditionally used tillage to control weeds in their fields, interrupting weed life cycles before they can produce seeds for the following year. However, using tillage to help manage weeds reduces soil quality and increases soil loss from erosion. Tilled soil forms a crust, which reduces the ability of water to infiltrate the surface and leads to runoff that can pollute surface water with sediments and chemicals. Conservation tillage, which leaves at least 30 percent of the previous crop’s residue on the field, improves soil quality and water infiltration and reduces erosion because more organic matter is left on the soil surface, thereby decreasing disruption of the soil. The adoption of HR crops
allows some farmers to substitute glyphosate application for some tillage operations as a weed-management tactic and thereby benefits soil quality and probably improves water quality, although definitive research on the latter is lacking. However, empirical evidence points to a two-way causal relationship between the adoption of HR crops and conservation tillage. Farmers who use conservation tillage are more likely to adopt HR crop varieties than those who use conventional tillage, and those who adopt HR crop varieties are more likely to practice conservation tillage than those who use non-GE seeds.

Finding 3. Targeting specific plant insect pests with Bt corn and cotton has been successful, and the ability to target specific plant pests in corn and cotton continues to expand. Insecticide use has decreased with the adoption of insect-resistant (IR) crops. The emergence of insect resistance to Bt crops has been low so far and of little economic or agronomic consequence; two pest species have evolved resistance to Bt crops in the United States.
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Bt toxins, which are produced by the soil-dwelling bacterium *Bacillus thuringiensis*, are lethal to the larvae of particular species of moths, butterflies, flies, and beetles and are effective only when an insect ingests the toxin. Therefore, crops engineered to produce Bt toxins that target specific pest taxa have had favorable environmental effects when replacing broad-spectrum insecticides that kill most insects (including beneficial insects, such as honey bees or natural enemies that prey on other insects), regardless of their status as plant pests. The amounts of insecticides applied per planted acre of Bt corn and cotton have inverse relationships with the adoption of these crops over time (Figures S-4 and S-5), though a causative relationship has not been established or refuted because other factors influence pesticide-use patterns.

Since their introduction in 1996, the use of IR crops has increased rapidly, and they continue to be effective. Data indicate that the abundance of refuges of non-Bt host plants and recessive inheritance of resistance are two key factors influencing the evolution of resistance. The refuge strategies mandated by the Environmental Protection Agency, and the promotion of such strategies by industry, likely contributed to increasing the use of refuges and to delaying the evolution of resistance to Bt in key pests.

**FIGURE S-4** Pounds of active ingredient of insecticide applied per planted acre and percent acres of Bt corn, respectively.

NOTE: The strong correlation between the rising percentage of Bt corn acres planted over time and the decrease in pounds of active ingredient per planted acre suggests but does not confirm causation between these variables.

Nevertheless, some populations of two generalist pests have evolved resistance to Bt crops in the United States, although the agronomic and economic consequences appear to be minor. With the introduction of multiple Bt toxins in new hybrids or varieties, the probability of resistance to Bt crops is further reduced.

**Finding 4.** For the three major GE crops, gene flow to wild or weedy relatives has not been a concern to date because compatible relatives of corn and soybean do not exist in the United States and are only local for cotton. For other GE crops, the situation varies according to species. However, gene flow to non-GE crops has been a concern for farmers whose markets depend on an absence of GE traits in their products. The potential risks presented by gene flow may increase as GE traits are introduced into more crops.

Gene flow between many GE crops and wild or weedy relatives is low because GE crops do not have wild or weedy relatives in the United States or because the spatial overlap between a crop and its relatives is not extensive. How that relationship changes will depend on what GE crops
are commercialized, whether related species with which they are capable of interbreeding are present, and the consequences of such interbreeding on weed management. Gene flow of approved GE traits into non-GE varieties of the same crops (known as adventitious presence) remains a serious concern for farmers whose market access depends on adhering to strict non-GE presence standards. Resolving this issue will require the establishment of thresholds for the presence of GE material in non-GE crops, including organic crops, that do not impose excessive costs on growers and the marketing system.

**Economic Effects**

The rapid adoption of GE crops since their commercialization indicates that the benefits to adopting farmers are substantial and generally outweigh additional technology fees for these seeds and other associated costs. The economic benefits and costs associated with GE crops extend beyond farmers who use the technology and will change with continuing adoption in the United States and abroad as new products emerge.

**Finding 5.** Farmers who have adopted GE crops have experienced lower costs of production and obtained higher yields in many cases because of more cost-effective weed control and reduced losses from insect pests. Many farmers have benefited economically from the adoption of Bt crops by using lower amounts of or less expensive insecticide applications, particularly where insect pest populations were high and difficult to treat before the advent of Bt crops.

The incomes of those who have adopted genetic-enginering technology have benefited from some combination of yield protection and lower costs of production. HR crops have not substantially increased yields, but their use has facilitated more cost-effective weed control, especially on farms where weeds resistant to glyphosate have not yet been identified. Lower yields were sometimes observed when HR crops were introduced, but the herbicide-resistant trait has since been incorporated into higher-yielding cultivars, and technological improvement in inserting the trait has also helped to eliminate the yield difference. In areas that suffer substantial damage from insects that are susceptible to the Bt toxins, IR crops have increased adopters’ net incomes because of higher yields and reduced insecticide expenditures. Before the introduction of Bt crops, most farmers accepted yield losses to European corn borer rather than incur the expense and uncertainty of chemical control. Bt traits to address corn rootworm problems have lowered the use of soil-applied and seed-applied insecticides. In areas of high susceptible insect populations, Bt
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http://www.nap.edu/catalog.php?record_id=12804

cotton has been found to protect yields with fewer applications of topical insecticides. More effective management of weeds and insects also means that farmers may not have to apply insecticides or till for weeds as often, and this translates into cost savings—lower expenditures for pesticides and less labor and fuel for equipment operations.

Finding 6. Adopters of GE crops experience increased worker safety and greater simplicity and flexibility in farm management, benefitting farmers even though the cost of GE seed is higher than non-GE seed. Newer varieties of GE crops with multiple GE traits appear to reduce production risk for adopters.

Farmers who purchase GE seed pay a technology fee—a means by which seed developers recover research and development costs and earn profits. GE seed is typically more expensive than conventional seed, and the net return in terms of higher yields and lower costs of production for a farmer considering adoption does not always offset the technology fee. However, studies have found that high rates of adoption of GE crops can be attributed in part to the value that farmers place on increased worker safety, perceived greater simplicity and flexibility in farm management (including more off-farm work opportunities), and lower production risk. Farmers and their employees not only face reduced exposure to the harsh chemicals found in some herbicides and insecticides used before the introduction of GE crops but have to spend less time in the field applying the pesticides. Because glyphosate can be applied over a fairly wide time-frame, farmers who use HR crops have greater flexibility regarding when they treat weeds in their fields. Those benefits must be balanced with the risk that such flexibility in application timing may reduce crop-yield potential attributable to weed interference. Newer GE varieties that have multiple pest-control traits may result in more consistent pest management and thus less yield variability, a characteristic that has substantial value for risk-averse producers. The value of those benefits may provide additional incentives for adoption that counteract the extra cost of GE seed.

Finding 7. The effect GE crops have had on prices received by farmers for soybean, corn, and cotton is not completely understood.

Studies suggest that the adoption of GE crops that confer productivity increases ultimately puts downward pressure on the market prices of the crops. However, early adopters benefit from higher yields or lower production costs more than nonadopters even with lower prices. The gains tend to dissipate as the number of adopters increases, holding techno-
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logical progress constant. Thus, as the first adopters, U.S. farmers have generally benefited economically from the fact that GE crops were developed and commercialized in the United States before they were planted by farmers in other countries. The extent to which GE-crop adoption in developing countries will influence productivity and prices, and therefore U.S. farm incomes, is not completely understood. There is a paucity of studies of the economic effects of genetic-engineering technology in recent years even though adoption has increased globally.

Finding 8. To the extent that economic effects of GE-crop plantings on non-GE producers are understood, the results are mixed. By and large, these effects have not received adequate research.

Decisions made by adopters of GE crops can affect the input prices and options for both farmers who use feed and food products made with GE ingredients and farmers who have chosen not to grow GE seed or do not have the option available. The effects on those not using genetic-engineering technology have not been studied extensively. Livestock producers constitute a large percentage of corn and soybean buyers and therefore are major beneficiaries of any downward pressure on crop price due to the adoption of GE crops. Feed costs are nearly half the variable costs for livestock producers, so even moderate price fluctuations can affect their net incomes substantially. Livestock producers also benefit from increased feed safety due to reduced levels of mycotoxins in the grain. However, no quantitative estimation of savings to livestock operators due to the adoption of GE crops and the resulting effect on the profitability of livestock operations has been conducted. Similarly, a number of other economic effects predicted by economic theory have not been documented.

Favorable and unfavorable externalities are not limited to the cost and availability of inputs. To the extent that genetic-engineering technology successfully reduces pest pressure on a field and regionally, farmers of fields in the agricultural landscape planted with non-GE crops may benefit via lower pest-control costs associated with reductions in pest populations. However, nonadopters of genetic-engineering technology also could suffer from the development of weeds and insects that have acquired pesticide resistance in fields within the region planted to GE crops. When that happens, farmers might have to resort to managing the resistant pests with additional, potentially more toxic or more expensive forms of control, even though their practices may not have led to the evolution of resistance.

Inadvertent gene flow from GE to non-GE varieties of crops can increase production costs. Gene flow occurs through cross-pollination between GE and non-GE plants from different fields, co-mingling of GE
seed with non-GE seed, and germination of seeds left behind (volunteers) after the production year. Similarly, if GE traits cross into weedy relatives, weed-control expenses will be higher for all fields on to which the weeds spread, whether a farmer grows GE crops or not. In addition, gene flow of GE traits into organic crops could jeopardize crop value by rendering outputs unsuitable for high-value foreign or other markets that limit or do not permit GE material in food products; the extent of that effect has not been documented during the last 5 years. On the other hand, the segregation of GE traits from organic production may have benefited organic producers by creating a market in which they can receive a premium for non-GE products.

Social Effects

The use of GE crops, like the adoption of other technologies at the farm level, is a dynamic process that both affects and is affected by the social networks that farmers have with each other, with other actors in the commodity chain, and with the broader community in which farm households reside. However, the social effects of GE-crop adoption have been largely overlooked.

Finding 9. Research on the dissemination of earlier technological development in agriculture suggests that favorable and unfavorable social impacts exist from the dissemination of genetic-engineering technology. However, these impacts have not been identified or analyzed.

Because GE crops have been widely adopted rapidly, it is reasonable to hypothesize that there have been social effects on adopters, non-adopters, and farmers who use GE products, such as livestock producers. For example, based on earlier research on the introduction of new technologies in agriculture, it is possible that certain categories of farmers (such as those with less access to credit, those with fewer social connections to university and private-sector researchers, or those who grow crops for smaller markets) might be less able to access or benefit from GE crops. The introduction of genetic-engineering technology in agriculture could also affect labor dynamics, farm structure, community viability, and farmers’ relationships with each other and with information and input suppliers. However, the extent of the social effects of the dissemination of GE crops is unknown because little research has been conducted.

Finding 10. The proprietary terms under which private-sector firms supply GE seeds to the market has not adversely affected the economic welfare of farmers who adopt GE crops. Nevertheless, ongoing research
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is needed to investigate how market structure may evolve and affect access to non-GE or single-trait seed. Furthermore, there has been little research on how increasing market concentration of seed suppliers affects overall yield benefits, crop genetic diversity, seed prices, and farmers’ planting decisions and options.

During the 20th century, the U.S. seed industry evolved from small, family-owned businesses that multiplied seeds developed by university scientists to a market dominated by a handful of large, diversified companies. Universities still contribute to seed development, but seed companies have invested considerably in the research, development, and commercialization of patent-protected GE traits for large seed markets. Thus, corn, soybean, and cotton have received the bulk of private research attention in the last few decades. Large seed companies have not commercialized GE traits in many other crops because their market size has been insufficient to cover necessary research and development costs or because of concerns related to consumer acceptance and gene flow. Public research institutions continue to enhance the genetics of other crops, but full access to state-of-the-art technology (like genetic engineering) that may be beneficial to crops in smaller markets is often not available to public researchers because of patent protections.

Studies conducted in the first few years after the introduction of GE crops found no adverse effects on farmers’ economic welfare from the consolidation of market power in the seed industry. However, the current developmental trajectory of GE-seed technology is causing some farmers to express concern that access to seeds without GE traits or to seeds that have only the specific GE traits that are of particular interest to farmers will become increasingly limited. Additional concerns are being raised about the lack of farmer input into and knowledge about which seed traits are being developed. Although the committee was not able to find published peer-reviewed material that documented the degree of U.S. farmers’ access to non-GE seed and the quality of the seed, testimony provided to the committee suggests that access to non-GE or nonstacked seed may be restricted for some farmers or that available non-GE or nonstacked seed may be available in older cultivars that do not have the same yield characteristics as newer GE cultivars.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 1. Weed problems in fields of HR crops will become more common as weeds evolve resistance to glyphosate or weed communities less susceptible to glyphosate become established in areas treated exclusively with that herbicide. Though problems of evolved resistance
and weed shifts are not unique to HR crops, their occurrence, which is documented, diminishes the effectiveness of a weed-control practice that has minimal environmental impacts. Weed resistance to glyphosate may cause farmers to return to tillage as a weed-management tool and to the use of potentially more toxic herbicides.

A number of new genetically engineered HR cultivars are currently under development and may provide growers with other weed-management options when fully commercialized. However, the sustainability of those new GE cultivars will also be a function of how the traits are managed. If they are managed in the same fashion as the current genetically engineered HR cultivars, the same problems of evolved herbicide resistance and weed shifts may occur. Therefore, farmers of HR crops should incorporate more diverse management practices, such as herbicide rotation, herbicide application sequences, and tank-mixes of more than one herbicide; herbicides with different modes of action, methods of application, and persistence; cultural and mechanical control practices; and equipment-cleaning and harvesting practices that minimize the dispersal of HR weeds.

Recommendation 1. Federal and state government agencies, private-sector technology developers, universities, farmer organizations, and other relevant stakeholders should collaborate to document emerging weed-resistance problems and to develop cost-effective resistance-management programs and practices that preserve effective weed control in HR crops.

Conclusion 2. Given that agriculture is the largest source of surface water pollution, improvements in water quality resulting from the complementary nature of herbicide-resistance technology and conservation tillage may represent the largest single environmental benefit of GE crops. However, the infrastructure to track and analyze these effects is not in place.

Recommendation 2. The U.S. Geological Survey and companion federal and state environmental agencies should receive the financial resources necessary to document the water quality effects related to the adoption of GE crops.

Conclusion 3. The environmental, economic, and social effects on adopters and nonadopters of GE crops has changed over time, particularly because of changes in pest responses to GE crops, the consolidation of the seed industry, and the incorporation of GE traits into most varieties of corn, soybean, and cotton. However, empirical research into the environmental and economic effects of changing market conditions and farmer practices have not kept pace. Furthermore, little work has
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been conducted regarding the effects on livestock producers and non-adopters and on the social impacts of GE crops. Issues in need of further investigation include the costs and benefits of shifts in pest management for non-GE producers due to the adoption of GE crops, the value of market opportunities afforded to organic farmers by defining their products as non-GE, the economic impacts of GE-crop adoption on livestock producers, and the costs to farmers, marketers, and processors of the presence of approved or unapproved GE traits and crops in products intended for restricted markets. As more GE traits are developed and inserted into existing GE crops or into other crops, understanding the impacts on all farmers will become even more important to ensuring that genetic-engineering technology is used in a way that facilitates environment, economic, and social sustainability in U.S. agriculture.

Recommendation 3. Public and private research institutions should allocate sufficient resources to monitor and assess the substantial environmental, economic, and social effects of current and emerging agricultural biotechnology on U.S. farms so that technology developers, policy makers, and farmers can make decisions that ensure genetic engineering is a technology that contributes to sustainable agriculture.

Conclusion 4. Commercialized GE traits are targeted at pest control, and when used properly, they have been effective at reducing pest problems with economic and environmental benefits to farmers. However, genetic engineering could be used in more crops, in novel ways beyond herbicide and insect resistance, and for a greater diversity of purposes. With proper management, genetic-engineering technology could help address food insecurity by reducing yield losses through its introduction into other crops and with the development of other yield protection traits like drought tolerance. Crop biotechnology could also address “public goods” issues that will be undersupplied by the market acting alone. Some firms are working on GE traits that address public goods issues. However, industry has insufficient incentive to invest enough in research and development for those purposes when firms cannot collect revenue from innovations that generate net benefits beyond the farm. Therefore, the development of these traits will require greater collaboration between the public and private sectors because the benefits extend beyond farmers to the society in general. The implementation of a targeted and tailored regulatory approach to GE-trait development and commercialization that meets human and environmental safety standards while minimizing unnecessary expenses will aid this agenda (Ervin and Welsh, 2006).
THE IMPACT OF GE CROPS ON FARM SUSTAINABILITY

Recommendation 4. Public and private research institutions should be eligible for government support to develop GE crops that can deliver valuable public goods but have insufficient market potential to justify private investment. Intellectual property patented in the course of developing major crops should continue to be made available for such public goods purposes to the extent possible. Furthermore, support should be focused on expanding the purview of genetic-engineering technology in both the private and public sectors to address public goods issues. Examples of GE-crop developments that could deliver such public goods include but are not limited to

- plants that reduce pollution of off-farm waterways through improved use of nitrogen and phosphorus fertilizers,
- plants that fix their own nitrogen and reduce pollution caused by fertilizer application,
- plants that improve feedstocks for renewable energy,
- plants with reduced water requirements that slow the depletion of regional water resources,
- plants with improved nutritional quality that deliver health benefits, and
- plants resilient to changing climate conditions.

REFERENCES


SUMMARY


THE IMPACT OF
GENETICALLY ENGINEERED CROPS
ON FARM SUSTAINABILITY
IN THE UNITED STATES

Committee on the Impact of Biotechnology on
Farm-Level Economics and Sustainability

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

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1The views expressed here are those of the authors and may not be attributed to the Economic Research Service or the U.S. Department of Agriculture.
Preface

Not since the introduction of hybrid corn seed have we witnessed such a sweeping technological change in U.S. agriculture. Hundreds of thousands of farmers have adopted the first generation of genetically engineered (GE) crops since their commercialization in 1996. Although not all GE varieties that have been commercialized have succeeded, those targeted at improved pest control now cover over 80 percent of the acres planted to soybean, cotton, and corn—that is, almost half of U.S. crop-land. Forecasts suggest an expansion in GE-crop plantings in many other countries.

GE crops originate in advances in molecular and cellular biology that enable scientists to introduce desirable traits from other species into crop plants or to alter crop plants’ genomes internally. Those powerful scientific techniques have dramatically expanded the boundaries that have constrained traditional plant breeding. A new technology adopted so widely and rapidly has substantial economic, social, and environmental impacts on farms and their operators. Inevitably, both advantages and risks or losses emerge from such massive changes. The National Research Council has conducted multiple studies of specific aspects of GE crops, such as regulatory-system adequacy and food safety. However, the assigned tasks restricted the scope of their reports. As pressure mounts to expand the use of GE crops for energy, food security, environmental improvement, and other purposes, the scope and intensity of impacts will grow. Now is an opportune time to take a comprehensive look at the track record of GE crops and to identify the opportunities and challenges loom-
ing on the horizon. The National Research Council therefore supported
the Committee on the Impact of Biotechnology on Farm-Level Economics
and Sustainability to investigate this topic.

Despite the rapid spread of GE crops in U.S. agriculture, the technol-
yogy continues to stir controversy around scientific issues and ideological
viewpoints. The committee focused on the scientific questions associated
with the farm-level impacts of the adoption of genetic-engineering tech-
nology and refrained from analyzing ideological positions, either pro or
con. The committee adopted an “evidentiary” standard of using peer-
reviewed literature on which to form our conclusions and recommenda-
tions. It is my hope that the report will give readers a firm grasp of the
state of evidence or lack thereof on the scientific issues.

True to its charge, the committee adopted a sustainability frame-
work that required an evaluation of environmental, economic, and social
impacts of GE crops. Those three dimensions constitute the essential
pillars of sustainability science. The summary and opening and closing
chapters bring together the three perspectives for a fuller view of the
technology’s impact.

Given the controversies, readers will want to know the committee’s
composition and how it conducted its work in arriving at conclusions
and recommendations. The biographies in Appendix C show a group of
highly accomplished natural and social scientists who possess a broad
array of research experience and perspectives on GE crops. That diversity
of disciplines and expertise proved beneficial in introducing checks and
balances in evaluating information from many angles. The committee
members divided into teams to work on the various sections of the report
on the basis of the members’ expertise. The drafts by each team were
reviewed by the full committee to ensure that everyone had a chance to
comment on and improve and approve each section. I was continually
impressed with the members’ dedication to a hard-nosed and impartial
evaluation of the best science on GE crops. Equally important, they kept
open minds in considering new evidence presented by their colleagues
and external experts. The result was a model multidisciplinary research
process in which each of us learned from the others and improved the
report quality.

In closing, I want to express my deep appreciation to the committee
members for their tireless work and good humor in completing such a
challenging task while working full time at their regular jobs. Their com-
mitment and professionalism exemplify the best of public science. Each
member made significant contributions to the final report. The commit-
tee also benefited from the testimony of several experts in the field and
from the numerous comments of many conscientious external reviewers.
Finally, the quality of the report would not have been attained without excellent support and substantive input by study director Kara Laney, the valuable assistance of Kamweti Mutu, the insightful counsel of Robin Schoen, and the editorial work of the National Research Council.

David E. Ervin, Chair  
Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability
Acknowledgments

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council Report Review Committee. The purpose of the independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of the report:

David A. Andow, University of Minnesota, St. Paul
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Washington

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of the report was overseen by Drs. Alan G. McHughen, University of California, Riverside, and May R. Berenbaum, University of Illinois, Urbana-Champaign. Appointed by the National Research Council, they were responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of the report rests with the authoring committee and the institution.
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Abbreviations and Acronyms

ACCase acetyl-CoA carboxylase
ALS acetolactate synthase
AMPA aminomethylphosphonic acid
APHIS Animal and Plant Health Inspection Service (U.S. Department of Agriculture)
BST bovine somatotropin
Bt Bacillus thuringiensis
Cry crystal-like (protein)
DNA deoxyribonucleic acid
EIS environmental impact statement
EPA U.S. Environmental Protection Agency
EPSPS enzyme 5-enolpyruvyl-shikimate-3-phosphate synthase
GE genetically engineered
GMO genetically modified organism
HPPD hydroxyphenylpyruvate dioxygenase
HR herbicide-resistant
IPR intellectual-property rights
<table>
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<tr>
<td>IR</td>
<td>insect-resistant</td>
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<tr>
<td>ISHRW</td>
<td>International Survey of Herbicide Resistant Weeds</td>
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<tr>
<td>MCL</td>
<td>maximum contaminant level</td>
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<tr>
<td>NOP</td>
<td>National Organic Program</td>
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<td>NOSB</td>
<td>National Organic Standards Board</td>
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<td>OFPA</td>
<td>Organic Foods Production Act</td>
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<tr>
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<td>U.S. Patent and Trademark Office</td>
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<td>R&amp;D</td>
<td>research and development</td>
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<td>USDA</td>
<td>U.S. Department of Agriculture</td>
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<tr>
<td>USDA-ERS</td>
<td>U.S. Department of Agriculture, Economic Research Service</td>
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<tr>
<td>USDA-NASS</td>
<td>U.S. Department of Agriculture, National Agricultural Statistics Service</td>
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<tr>
<td>VR</td>
<td>virus-resistant</td>
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