FAILURE TO YIELD

Evaluating the Performance of
Genetically Engineered Crops

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

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UCS is the leading science-based nonprofit working for a healthy environment and a safer world.

The goal of the UCS Food and Environment Program is a food system that encourages innovative and environmentally sustainable ways to produce high-quality, safe, and affordable food, while ensuring that citizens have a voice in how their food is grown.

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Executive Summary

Driven by economic and political forces, food prices soared to record highs in 2007 and 2008, causing hardships around the world. Although a global food shortage was not a factor then or now—worldwide food production continues to exceed demand—those recent price spikes and localized scarcity, together with rising populations in many countries and individuals' rising aspirations, have brought renewed attention to the need to increase food production in the coming decades. Many commentators and stakeholders have pointed to the alleged promise of genetic engineering (GE)—in which the crop DNA is changed using the gene-insertion techniques of molecular biology—for dramatically improving the yields of staple food crops. But a hard-nosed assessment of this expensive technology's achievements to date gives little confidence that it will play a major role in helping the world feed itself in the foreseeable future.

This report is the first to evaluate in detail the overall, or aggregate, yield effect of GE after more than 20 years of research and 13 years of commercialization in the United States. Based on that record, we conclude that GE has done little to increase overall crop yields.

How Else Can Farmers Increase Production?

Among the many current approaches are crop breeding; chemical fertilizers, herbicides, and pesticides; crop rotation; and organic methods, which ensure the health of the soil. Nevertheless, GE crops have received by far the most attention since they were commercially introduced in the mid-1990s. Ever since, the biotech industry and others have trumpeted them as key to feeding the world's future population.

The two primary GE food and feed crops are corn and soybeans. GE soybeans are now grown on over 90 percent of soybean acres, and GE corn makes up about 63 percent of the U.S. corn crop. Within these categories, the three most common GE crops are: (1) corn containing transgenes (genes transferred from another organism using genetic engineering) from *Bt (Bacillus thuringiensis)* bacteria that confer resistance to several kinds of insects; (2) corn containing transgenes for herbicide tolerance; and (3) soybeans that contain a transgene for herbicide tolerance. Now that these transgenic crops have been grown in the United States for more than a decade, there is a wealth of data on yield under real-world conditions. Thus a close examination of numerous studies of corn and soybean crop yields since the early 1990s gives us a good gauge of how well GE crops are living up to their promise for increasing those yields.

Bottom line: They are largely failing to do so. GE soybeans have not increased yields, and GE corn has increased yield only marginally on a crop-wide basis. Overall, corn and soybean yields have risen substantially over the last 15 years, but largely not as result of the GE traits. Most of the gains are due to traditional breeding or improvement of other agricultural practices.

While the need to increase food production is expected to become more urgent, awareness of the complex interactions between agriculture and the environment is also on the rise. Many of the predicted negative effects of global warming—including greater incidence and severity of drought, flooding, and sea-level rise (which may swamp coastal farmland)—are likely to make food production more challenging. At the same time, it is becoming clear that the twentieth century's

industrial methods of agriculture have imposed tremendous costs on our environment. Agriculture contributes more heat-trapping gases than does transportation, and it is a major source of pollution that has led to large and spreading "dead zones" devoid of fish and shellfish (themselves important food sources) in the Gulf of Mexico and other waterways. As we strive to produce more food, we must seek to do it in an efficient and sustainable manner—that is, in ways that do not undermine the foundation of natural resources on which future generations will depend.

Defining Yield(s)

It is crucial to distinguish between two kinds of yield—intrinsic yield and operational yield—when evaluating transgenic crops. Intrinsic yield, the highest that can be achieved, is obtained when crops are grown under ideal conditions; it may also be thought of as potential yield. By contrast, operational yield is obtained under field conditions, when environmental factors such as pests and stress result in yields that are considerably less than ideal. Genes that improve operational yield reduce losses from such factors.

But while operational yield is important, better protecting crops from pests and stress without increasing potential yield will not do enough to meet the future food needs of an expanded population. Food-crop breeders must deliver improvements both in intrinsic yield and operational yield to keep up with growing demand.

In this report, the record of commercialized GE crops in producing increases both in intrinsic and operational yield is assessed. We rely heavily on experiments conducted by academic scientists, using adequate experimental controls, and published in peer-reviewed journals. These studies, many of them recent, evaluate GE traits against other conventional farming practices. In some cases, the results of earlier widely cited reports are superseded by these more recent data.

The success of GE technology in producing new yield traits is also evaluated by examining specific transgenes associated with yield that have been tested in experimental field trials over the past two decades. This focus also provides a measure of the effort by the biotechnology industry and others to increase crop yield through GE means.

The Findings

1. Genetic engineering has not increased intrinsic yield.

No currently available transgenic varieties enhance the intrinsic yield of any crops. The intrinsic yields of corn and soybeans did rise during the twentieth century, but not as a result of GE traits. Rather, they were due to successes in traditional breeding.

2. Genetic engineering has delivered only minimal gains in operational yield.

Herbicide-Tolerant Soybeans and Corn. Although not extensive enough to develop precise yield estimates, the best data (which were not included in previous widely cited reviews on yield) show that transgenic herbicide-tolerant soybeans and corn have not increased operational yields, whether on a per-acre or national basis, compared to conventional methods that rely on other available herbicides. The fact that the herbicide-tolerant soybeans have been so widely adopted suggests that factors such as lower energy costs and convenience of GE soybeans also influence farmer choices.

Bt Corn to Control Insect Pests. *Bt* corn contains one or more transgenes primarily intended to control either the European corn borer (this corn was first commercialized in 1996) or corn rootworm species (commercialized in 2004). Based on available data, it is likely that *Bt* corn provides an operational yield advantage of 7–12 percent compared to typical conventional practices, including insecticide use, when European corn borer infestations are high. *Bt* corn offers little or no advantage when infestations of European corn borer are low to moderate, even when compared to conventional corn not treated with insecticides.

Evaluating operational yield on a crop-wide basis, at either a national or global scale, is needed to determine overall food availability. Given that

about a third of the corn crop in the United States is devoted to European corn borer *Bt* varieties, using the yield data summarized above we estimate that the range of yield gain averaged across the entire corn crop is about 0.8–4.0 percent, with a 2.3 percent gain as a reasonable intermediate value.

Similar calculations can be made for *Bt* rootworm corn. One of the few estimates from the literature suggests that *Bt* rootworm corn provides about a 1.5–4.5 percent increase in operational yield compared to conventional corn treated with insecticides. Extensive field experiments in Iowa, mostly with heavy rootworm infestations, show a range of values not inconsistent with these estimates. Given that *Bt* rootworm corn is probably planted on up to a third of corn acres, the aggregate operational yield advantage for these varieties averaged over all corn acres is roughly 0.5–1.5 percent.

Combining the values for *Bt* European corn borer corn and *Bt* rootworm corn gives an estimated operational yield increase from the *Bt* traits of 1.3–5.5 percent. An increase of about 3.3 percent, or a range of 3–4 percent, is a reasonable intermediate. Averaged over the 13 years since *Bt* corn was first commercialized in 1996, this equates roughly to a 0.2–0.3 percent yield increase per year.

3. Most yield gains are attributable to non-genetic engineering approaches.

In the past several decades, overall corn yields in the United States have increased an average of about 1 percent per year, or considerably more in total than the amount of yield increase provided by *Bt* corn varieties. More specifically, U.S. Department of Agriculture data indicate that the average corn production per acre nationwide over the past five years (2004–2008) was about 28 percent higher than for the five-year period 1991–1995, an interval that preceded the introduction of *Bt* varieties.[1] But our analysis of specific yield studies concludes that only 3–4 percent of that increase is attributable to *Bt*, meaning an increase of about

24–25 percent must be due to other factors such as conventional breeding.

Yields have also continued to increase in other major crops, including soybeans (which have not experienced increases in either intrinsic or operational yield from GE) and wheat (for which there are no commercial transgenic varieties). Comparing yield in the latter period with that of the former, the increases were about 16 percent for soybeans and 13 percent for wheat. Overall, as shown above, GE crops have contributed modestly, at best, to yield increases in U.S. agriculture.

Organic and low-external-input methods (which use reduced amounts of fertilizer and pesticides compared to typical industrial crop production) generally produce yields comparable to those of conventional methods for growing corn or soybeans. For example, non-transgenic soybeans in recent low-external-input experiments produced yields 13 percent higher than for GE soybeans, although other low-external-input research and methods have produced lower yield.

Meanwhile, conventional breeding methods, especially those using modern genomic approaches (often called marker-assisted selection and distinct from GE), have the potential to increase both intrinsic and operational yield. Also, more extensive crop rotations, using a larger number of crops and longer rotations than current ecologically unsound corn-soybean rotations, can reduce losses from insects and other pests.

4. Experimental high-yield genetically engineered crops have not succeeded.

Several thousand experimental GE-crop field trials have been conducted since 1987. Although it is not possible to determine the precise number of genes for yield enhancement in these trials, given the confidential-business-information concerns among commercial developers, it is clear that many transgenes for yield have been tested over the years.

Among these field trials, at least 3,022 applications were approved for traits such as disease

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[1] Operational and intrinsic yields cannot be distinguished in these aggregate yield numbers.

resistance or tolerance to abiotic stress (e.g., drought, frost, floods, saline soils). These traits are often associated with yield.[2] At least 652 of the trials named yield as the particular target trait. Only the *Bt* and herbicide-tolerance transgenes and five transgenes for pathogen resistance have been commercialized, however, and only *Bt* has had an appreciable impact on aggregate yields.[3]

Some of these transgenes may simply not be ready for prime time. It typically takes several years of field trials and safety testing before a transgenic crop is approved and ready to be grown by farmers. However, 1,108 of these field trials were approved prior to 2000, not including those for insect resistance or herbicide tolerance. Most of these earlier transgenic crops should have been ready for commercialization by the time of this report.

To summarize, the only transgenic food/ feed crops that have been showing significantly improved yield are varieties of *Bt* corn, and they have contributed gains in operational yield that were considerably less over their 13 years than other means of increasing yield. In other words, of several thousand field trials, many of which have been intended to raise operational and intrinsic yield, only *Bt* has succeeded. This modest record of success should suggest caution concerning the prospects for future yield increases from GE.

What *Are* Genetic Engineering's Prospects for Increasing Yield?

Genetic engineers are continuing to identify new genes that might raise intrinsic and operational yields. How likely is it that these genes will in fact produce commercially viable new crop varieties?

Research on theoretical limitations of plant physiology and morphology (form)—regarding the conversion of sunlight, nutrients, carbon dioxide, and water into food or feed—indicates how much intrinsic yield may be increased. While opinions differ about the possibility of achieving dramati-

cally increased yields through improvements in plant form and the processes listed above, optimistic estimates suggest that yield gains of up to about 50 percent over the next several decades may be achievable and that GE technology may play a prominent role.

These dramatic projections do not consider a fundamental reason why they may not be easy to achieve, especially regarding GE. Most of the transgenes being considered for the future, unlike the ones in currently commercialized transgenic crops, influence many other genes, thereby resulting in more complex genetic effects. Such genes typically have multiple effects on a crop, and early research is confirming that some of these effects can be detrimental, maybe even preventing the crops' commercialization altogether. Because such effects will not always be identified by testing under current regulations, improved regulations will be needed to ensure that harmful side effects are discovered and prevented.

In other words, even where these genes work as expected, they may still cause significant environmental or human health impacts, or have reduced agricultural value in some environments. And many of these genes will not address the negative impact of current industrial agriculture, and may even exacerbate these harmful effects if higher yield requires more fertilizer or pesticide use.

Given the variety of transgenes tested and the large amounts of research funding devoted to them, it would not be unexpected that some of them may eventually be successful in increasing yield. But in light of the complexity of their biochemical and physiological interactions, and their unpredictable side effects, it is questionable how many will become commercially viable.

Summary and Recommendations

The burgeoning human population challenges agriculture to come up with new tools to increase

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2   Insect resistance and herbicide tolerance are not included in these numbers because many of those trials include *Bt* and herbicide-tolerance genes that have been commercialized.
3   Virus-resistant GE papaya has prevented substantial yield loss, but it is grown only on several thousand acres in Hawaii and therefore has not contributed significantly to overall agricultural yield in the United States.

crop productivity. At the same time, we must not simply produce more food at the expense of clean air, water, soil, and a stable climate, which future generations will also require. In order to invest wisely in the future, we must evaluate agricultural tools to see which ones hold the most promise for increasing intrinsic and operational yields and providing other resource benefits.

It is also important to keep in mind where increased food production is most needed—in developing countries, especially in Africa, rather than in the developed world. Several recent studies have shown that low-external-input methods such as organic can improve yield by over 100 percent in these countries, along with other benefits. Such methods have the advantage of being based largely on knowledge rather than on costly inputs, and as a result they are often more accessible to poor farmers than the more expensive technologies (which often have not helped in the past).

So far, the record of GE crops in contributing to increased yield is modest, despite considerable effort. There are no transgenic crops with increased intrinsic yield, and only *Bt* corn exhibits somewhat higher operational yield. Herbicide-tolerant soybeans, the most widely utilized GE crop by far, do not increase either operational or intrinsic yield.

Genetic engineers are working on new genes that may raise both intrinsic and operational yield in the future, but their past track record for bringing new traits to market suggests caution in relying too heavily on their success.

It is time to look more seriously at the other tools in the agricultural toolkit. While GE has received most of the attention and investment, traditional breeding has been delivering the goods in the all-important arena of increasing intrinsic yield. Newer and sophisticated breeding methods using increasing genomic knowledge—but not GE—also show promise for increasing yield.

The large investment in the private sector ensures that research on GE versions of major crops will continue, while organic and other agro-ecological methods are not likely to attract a similar investment.

But given the modest yield increases from transgenic crops so far, putting too many of our crop-development eggs in the GE basket could lead to lost opportunities. Thus it is very important to compare the potential contributions of GE with those of other approaches, such as organic methods, low-input methods, and enhanced conventional-breeding methods. Where these alternatives look more promising, we should provide sufficient public funding to ensure that they will be available. Such prioritization is especially appropriate for research aimed at developing countries, where yield increases are most needed.

To ensure that adequate intrinsic and operational yields are realized from major crops in the coming years, the Union of Concerned Scientists makes the following recommendations:

- The U.S. Department of Agriculture, state and local agricultural agencies, and public and private universities should redirect substantial funding, research, and incentives toward approaches that are proven and show more promise than genetic engineering for improving crop yields, especially intrinsic crop yields, and for providing other societal benefits. These approaches include modern methods of conventional plant breeding as well as organic and other sophisticated low-input farming practices.

- Food-aid organizations should work with farmers in developing countries, where increasing local levels of food production is an urgent priority, to make these more promising and affordable methods available.

- Relevant regulatory agencies should develop and implement techniques to better identify and evaluate potentially harmful side effects of the newer and more complex genetically engineered crops. These effects are likely to become more prevalent, and current regulations are too weak to detect them reliably and prevent them from occurring.

Chapter 1

Introduction

In light of a burgeoning global population, the public is becoming more and more aware that an adequate food supply cannot be taken for granted. Thus the question of sufficient agricultural productivity, or yield—defined as the amount of a crop produced per unit of land over a specified amount of time—has received considerable attention, especially given already reported episodes of reduced food availability in some parts of the world. Although current food production is actually adequate when measured on a global scale, with issues other than agricultural yield being of greatest importance at present for determining access to food, ample production for 9 or 10 billion people by mid-century poses a challenge. Producing enough food while minimizing the environmental harm caused by current industrial farming methods and supporting rural communities could well become more pressing, especially as climate change proceeds.

Increasing farmlands' productivity is of course a main goal of agricultural research, especially regarding countries that currently do not produce enough food for local populations.[4] In the United States, the yields of major crops such as corn, wheat, and soybeans increased for most of the twentieth century as a result of conventional breeding and other technological changes, showing that the yield-improvement goal has been with us a long time.

Among the possible ways of raising productivity, genetic engineering (GE) has been promoted in recent years by the biotechnology industry as a revolutionary new way to produce crops with dramatically increased yields (Biotechnology Industry Organization 2009; Fernandez-Cornejo and Caswell 2006; McLaren 2005; Barboza 1999; Ibrahim 1996). Few studies, however, have attempted to summarize the relevant research on the actual impact of current GE traits on yield. This report examines that impact relative to corn and soybeans—the two primary GE food/feed crops—in the United States, and it evaluates the record of experimental GE crops as an indication of the industry's effort to try to increase yield. It also examines GE's yield-enhancement prospects for the next 5 to 10 years, based on current understanding of the biology of yield and the capabilities of GE.

In exploring how increased yield may be achieved, it is useful to distinguish between the potential yield of the crop, as when it is grown under ideal conditions, compared to actual yields in real environments. Potential yield, also referred to as intrinsic yield, is useful to consider as a benchmark for the highest yields that the genetics of the crop may allow. By contrast the actual, or operational, yield is achieved after the damages from pests (broadly defined) and abiotic stresses (e.g., drought, frost, floods, saline soils) are taken into account. Operational yield may also reflect inadequate inputs (of fertilizer, for example), which prevent the full promise of the crop from being realized. Both potential yield and operational yield may be addressed by technologies such as conventional breeding, GE, or other methods. For example, pest impacts may be reduced by the use of pesticides or crop rotations, while drought impacts may be reduced by increasing the efficiency of irrigation or by improving the water-retaining properties of the soil.

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[4] A more relevant measure may be the total yield of *all* crops produced on a unit of land over a specified period of time, which can take into account their multiple productivities. But in this report, where single crop species are considered, productivity applies only to one crop at a time.

This report is the first to evaluate in detail the overall, or aggregate, yield effect of GE after more than 20 years of research and 13 years of commercialization in the United States. Overall crop yield, or aggregate yield, is an important measure of crop productivity, indicating how much a technology contributes to increasing the amount of the crop that can potentially be used as food or livestock feed for entire populations. For example, a technology that produces a large yield benefit only on a small fraction of crop acres has a minor impact on food production, while a relatively small unit yield increase applied to the entire crop may substantially increase food supply. Thus although higher yield for individual farmers can be an important benefit for them, it tells us little about whether GE is substantially benefiting society.

In addition to providing insights on yield, examination of GE crops can provide some measure of the potential of the technology to successfully address other agricultural issues of great importance to society. These include water use, pollution, climate change, and nutrition.

A socially relevant evaluation of any technology must also consider how it stacks up against alternatives. Limits on available public resources suggest that we should allocate investments according to our best judgments on what practices, or mix of practices, is most likely to provide the greatest total value. In this report, the relative values of some alternatives to GE are therefore briefly considered.

Regardless of past performance, GE is a relatively new technology that may improve over time. From this perspective, it is also useful to consider anticipated advances in the technology; this may help us to understand not only the potential of GE to raise crop yields in the future but also the kinds of social structures that would allow society to use the technology more effectively. This report therefore ends with a brief consideration of the potential for GE to enhance yield, and of the inherent challenges, over the next several years.

Chapter 2

Background and Context

Increasing yield has long been a major motivation of agricultural research in the United States. As data from the U.S. Department of Agriculture (USDA) show, yields of major field (or commodity) crops such as corn, wheat, and soybeans have been rising steadily since early in the twentieth century. For example, corn yields improved by several percent per year through mid-century, though more slowly over the past several decades, as illustrated by Figure 1 (National Agricultural Statistics Service 2009). Today's average corn yields of about 150–160 bushels per acre are some six-fold higher than corn yields in 1930. Although not as dramatic, yields of wheat and soybeans have also risen consistently for decades.

It has been estimated that plant breeding accounted for about half of these yield increases, with the other half attributable to improvements in irrigation, mechanization, and fertilizer use (Duvick 2005). Because commercialized GE crops did not enter the market until the mid-1990s, it is clear that most of the historical yield increases attributable to breeding in field crops have resulted from conventional methods—in which observable traits such as disease resistance or stand density have been added to crops through direct selection by plant breeders. For example, wheat diseases once dramatically reduced wheat yields, with leaf rust alone causing declines of up to 40 percent. These diseases have been effectively controlled for decades by incorporating resistance genes from some wheat varieties or wild wheat relatives into commercially important wheat varieties. Breeding for many other traits that increase operational or intrinsic yield has been accomplished for all field crops.

Figure 1. U.S. Corn Yield
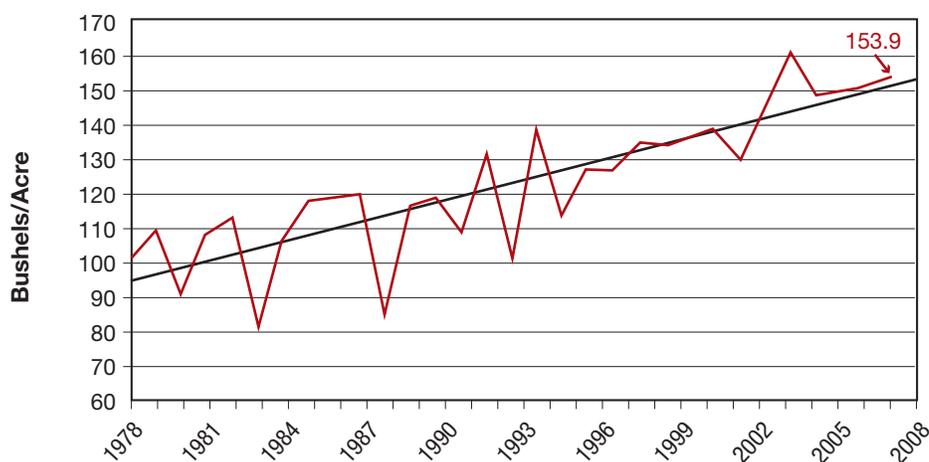
Source: National Agricultural Statistics Service 2009.

Pests and abiotic stresses, however, still account for substantial yield losses in the United States. This can be observed in the often-substantial variation in yield from year to year in the U.S. yield data (Figure 1). Because the yield potentials of crop varieties do not generally decrease, the large variation observed over short periods is largely due to impacts on operational yield. As seen from these data, the reductions compared to typical yields may be substantial. Therefore reducing yield loss to pests and abiotic stress continues to provide an opportunity for productivity improvement.

Typical yields may also be compared to record high yields, which represent crop production under highly favorable conditions that may even approach the variety's or crop species' yield potential. The record yields of corn in the United States have not changed much over the past 20–30 years, leading to suggestions that the yield potential may not have changed significantly for crops such as corn over that period of time (Duvick and Cassman 1999). The overall rate of U.S. yield increase has generally slowed over recent decades to about 1 percent per year (Duvick and Cassman 1999).

Observations of the declining rate of yield increase have also led to consideration of major crops' maximum yield potentials and how much of that potential may have already been achieved. It has also raised the question of what aspects of the crop or environment may be changed to further increase yields. For example, maximum incident light at a given latitude, the capacity of the plant to capture light energy to power photosynthesis, and the ability of the plant to partition captured light energy into desired plant products (such as grain) represent limits to increasing yield. Understanding such factors helps to illustrate the challenges for increasing yields in coming years and will be considered in this report's chapter on the future prospects of GE.

Increasing crop yields may be accompanied by unintended and undesirable impacts on the environment or human health. The rise in U.S.

yields has in fact resulted in greatly increased water and air pollution and reductions in biodiversity, as chemical inputs to enhance yield have also increased. Thus it is critically important to consider how the implementation of various methods to increase yield may also cause adverse side effects.

In typical Midwest corn production, synthetic nitrogen fertilizer is used to increase yield, but only about 30–50 percent of the added nitrogen is utilized by the crop (Tilman et al. 2002). The rest ends up in groundwater or surface water, as air pollution, or converted back to nitrogen gas (largely inert, and the main component of the atmosphere) by microbiological processes that occur in the soil (Kulkarni, Groffman, and Yavitt 2008). Additional yield increases may require increased amounts of fertilizer unless accompanied by greater nitrogen-use efficiency by the crop. And depending on the type of changes in the physiology of the crop, such increases in fertilizer may provide diminishing returns—where less of the added nitrogen is used by the crop, leaving more to cause environmental degradation (Tilman et al. 2002, Figure 2).

Water pollution caused by nitrogen and phosphorus fertilizers degrades water quality, contributing to "dead zones"—in the Gulf of Mexico and many other bodies of water—where oxygen levels are too low to support commercially valuable fish and other sea life (Rabalais et al. 2001; Turner and Rabalais 1994). Nitrogen fertilizers are also the primary source of anthropogenic nitrous oxide (N_2O), which is a heat-trapping gas some 300 times more potent than carbon dioxide. It is estimated that agriculture contributes about 10–12 percent of anthropogenic global warming emissions worldwide (Smith et al. 2007), and considerably more when the indirect effects of the conversion of forests and grasslands to crops are considered. Animal agriculture, the primary user of major grain crops such as corn and soybeans, also contributes to air and water pollution. For example, it is the primary source of airborne ammonia (from manure mostly produced by confined

Figure 2. Diminishing Returns on Nitrogen Fertilizer Application
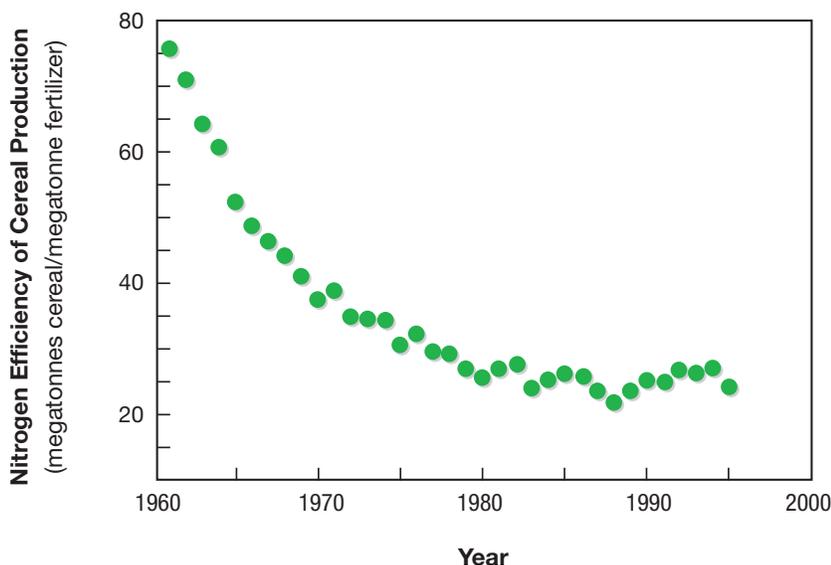
Source: Tilman et al. 2002.

animal feeding operations, or CAFOs), which contributes to acid precipitation and fine particulates. Acid precipitation harms forests and other natural ecosystems, and particulates are a major cause of respiratory diseases (McCubbin et al. 2002; Vitousek et al. 1997).

Consider the open question "How much does crop productivity need to increase in order to ensure adequate nutrition worldwide?" Many studies estimate that food production will need to grow 100 percent, despite projected population increases of about 50 percent; such projections are driven primarily by rising levels of global affluence, leading to increasing per capita demand for meat, milk, and eggs (McCalla 1994). Although these animal products provide high-quality protein, they also require much greater resource use and produce much more pollution and global warming emissions per unit of production compared to grains and legumes. Approximately 7–10 pounds of grain are required to produce one pound of

beef, 4–6 pounds to produce a pound of pork, and 2–3 pounds to produce a pound of chicken (e.g., Pimentel and Pimentel 2003). Thus the quest for higher meat and dairy consumption in the developing world is colliding with emerging concerns about their environmental effects. High levels of meat consumption in the United States are also associated with rising levels of obesity and related adverse health consequences. Therefore reduction in meat consumption, particularly in the developed countries (where such consumption is especially high), could result in substantially reducing the projected requirements for increased food production as well as in improving public health.

Simply producing adequate amounts of food per se is not sufficient to provide adequate nutrition for everyone. During the recent food crisis, enough nourishment was available worldwide to feed everyone, yet the United Nations estimated that the number of food-insecure people increased to 923 million in 2007 (Food and Agriculture

Organization 2008). Food must be readily available not only to those who can purchase it but also to the poor, and this involves issues of economics, political inequality, and distribution in addition to food production.

One way for such an outcome to occur is by raising production in developing countries, where the need is greatest, and by having small farmers produce adequate amounts of food locally. This issue is beyond the scope of the current report, but several recent studies suggest that dramatic increases in food production in developing countries can be achieved most quickly and most affordably by applying the principles of agro-ecology (Beintema et al. 2008; Badgley et al. 2007). A recent analysis of 114 research projects involving the yields of organic and near-organic farming methods found yield increases averaged 116 percent across Africa compared to yields obtained by farmers prior to the projects (Hines and Pretty 2008). Recent analysis also suggests that organic sources may be able to deliver enough nitrogen to crops, contrary to previous concerns (Badgley et al. 2007).

Finally, under the influence of the environment, food production is dynamic—climate change in particular may have substantial impacts on crop productivity by altering weather patterns. We must therefore consider how climate change may affect crop yields as it proceeds. Higher temperatures, for example, may increase yield in a few areas, but in most places yields could decline (Battisti and Naylor 2009).

Of the many aspects of agriculture that may be affected by changes in climate, one of the most fundamental is water use. Because agriculture already accounts for about 70 percent of human freshwater use (Seckler et al. 1998), the availability of adequate water for all future agricultural needs, including irrigation, looms as a growing problem. Similarly, weather generally has significant impacts on crop productivity—for example, through drought, flooding, and extreme temperature—which will be exacerbated by climate change. And rising sea levels will flood many coastal areas that are currently in productive agricultural service.

Chapter 3

Genetic Engineering and Yield: What Has the Technology Accomplished So Far?

Many have claimed that current GE crops increase yield (for example, Biotechnology Industry Organization 2009; Fernandez-Cornejo and Caswell 2006; McLaren 2005; Barboza 1999; Ibrahim 1996). To evaluate these claims we need to be clear on whether they apply to potential or operational yield, and we need to examine GE crops for which there are sufficiently robust data to draw reliable conclusions. Several *Bt* genes—insecticidal genes from the bacterium *Bacillus thuringiensis*—for achieving insect resistance in corn, as well as GE methods for instilling herbicide tolerance (HT) in corn and soybeans, have been widely commercialized for up to 13 years in the United States. These crops provide the best available test for the impact on yield of GE technology.

In addition to these few currently commercialized GE traits, many transgenes (genes transferred from one organism to another through GE) have been tested at various times over the past 20 years in field trials regulated by the USDA. Many of these latter genes encode traits that are typically aimed at improving yield. The number of field trials for these traits indicates the industry's determination to develop transgenic crops with higher yields, and the number of these experimental genes that go on to commercialization reveals the rate of success.

Intrinsic or Potential Yield

As discussed above, the two major types of traits now present in transgenic crops—insect resistance and herbicide tolerance—are often classic contributors to operational yield. Neither trait would be expected to enhance potential or intrinsic yield, and indeed there is virtually no evidence that they have done so.

Thus commercial GE crops have made no inroads so far into raising the intrinsic or potential yield of any crop. By contrast, traditional breeding has been spectacularly successful in this regard; it can be solely credited with the intrinsic-yield increases in the United States and other parts of the world that characterized the agriculture of the twentieth century.

Operational Yield: Comparative Studies on Commercialized Genetically Engineered Food and Feed Crops

While GE crops have been commercialized since the mid-1990s, only two types have been widely grown—corn and cotton containing *Bt* insecticidal genes, and corn, cotton, canola, and soybeans containing genes for herbicide tolerance. *Bt* genes in corn have targeted either Lepidoptera (primarily the larvae of the European corn-borer moth) or, more recently, the larvae of the corn rootworm beetles (Coleoptera). As of 2008, transgenic HT soybeans contained genes for tolerance to glyphosate-containing herbicides while transgenic HT corn contained genes for glyphosate or glufosinate tolerance.

Evaluation of Comparative Studies: The Importance of Appropriate Data

By design, *Bt* and HT—the two major transgenes in GE crops—would be expected to produce increases in operational yield in crops despite the presence of insect pests or weeds. To determine the

contribution of these transgenes to yield, research must be able to isolate their effects from the many other factors that influence yield. These factors include the overall genetic makeup of the crop variety—often, as the result of conventional breeding—along with specific growing conditions and practices such as pesticide use, crop rotations, irrigation, soil quality, and weather. For studies to accurately attribute yield increases to transgenes, they must try to control or account for these factors.

There are many approaches to measuring yield and to comparing the yield performance of one agricultural production method or technology to another. Different methods vary in their ability to accurately assess the contribution of the transgene—as opposed to other factors—to the yield of the crop. It is therefore important to consider the methodologies used in studies that measure and compare yield in GE crops.

Claims about the yield impact of transgenic crops have often been made based on inappropriate data. For example, substantial yield increase from GE has been suggested based on observations of broad yield trends (McLaren 2005) that do not adequately consider the many other important influences on yield, such as the varying impact of weather and the continuing advances from conventional breeding.

For this report we have searched for the most reliable and best-controlled studies we could find. Most of the studies selected were based on comparative field trials that attempted to control for non-GE variables.

One important such variable reflects the background genetic differences (other than the transgene) between crop varieties. Several studies have actually found that background genetics is often more critical than the transgene for determining yield (Jost et al. 2008; Meredith 2006). But when high-yielding varieties also contain a transgene, higher yield may be inaccurately attributed to GE

if care is not taken in designing the experiments. The converse situation may also occur. Ideally, the background genetics of the GE and non-GE varieties should be identical except for the presence or absence of the transgene. In practice, however, such complete genetic identity is not possible, though it can be approximated in so-called "near-isogenic" (NI) varieties.[5]

In addition to an inherent lack of complete identity, further breeding may cause the NI varieties to differ from their first-developed versions. Research conducted in Iowa, for example, found that one type of *Bt* corn resistant to corn rootworm had higher yields than the NI variety in the absence of pest infestation (Tollefson 2006). This suggests that further breeding of the *Bt* variety had produced higher yields independent of the transgenes. In general, however, use of NI varieties provides better control for genetic background than use of varieties that are not near-isogenic.

Field trials have their own limitations for predicting commercial-scale yield. Their limited duration and small size often do not adequately account for variability in weather, local pest species and amounts, crop rotations, and other factors that differ with place and time. For these reasons, multiple field trials at different locations and at different times are most useful, but remain only an approximation of the actual conditions of commercial agriculture.

To be of greatest practical value, the methods typically practiced by farmers should be used in field trials for comparison with the GE crop (Jost et al. 2008). For example, because conventional farmers sometimes use chemical insecticides to control moderate to heavy infestations of corn borer, it is most useful to compare a *Bt* crop to an untreated, NI, non-*Bt* control crop and also to treatments using typical corn borer insecticides. This would be representative of in-use farming methods and therefore would more accurately

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5   Near-isogenic varieties are also called isolines or isogenic in the literature. We prefer the term near-isogenic because it makes explicit the fact that the varieties are not truly identical.

reflect yield benefits on actual farms. Organic farmers, meanwhile, rely on crop rotation, soil quality, and other cultural methods to control insect pests, and therefore it is not accurate to consider an untreated non-*Bt* control crop that is otherwise grown using conventional industrial farming practices as a stand-in for organic farming.

In field trials that test traits expected to control pests, it is important to compare crops challenged with sufficient levels of the pest in at least some of the trials. Low levels of pests often do not provide a stringent-enough challenge to enable differentiation between methods.

Although there are no methods that are free from limitations, those that are likely to be hampered by the fewest problems are emphasized in this report where possible.

Herbicide-Tolerant Soybeans: Operational Yield in the Presence of Weeds

Soybeans tolerant of the herbicide glyphosate were introduced to U.S. farmers in 1996 and rapidly gained market share. Glyphosate-tolerant (GT) soybeans now constitute over 90 percent of all soybeans planted in the United States and represent the greatest proportion among GE crops. It is widely agreed that the ability to apply glyphosate to soybeans has provided greater convenience to farmers and reduced the time and costs relative to those of the herbicides previously used. But is any of this success attributable to increased yields in glyphosate-tolerant soy?

A number of studies have examined the yield of GT soybeans, several of which were included by the USDA in a recent report (Fernandez-Cornejo and Caswell 2006). Three of the studies compared yield for GT soybeans to non-GT, with two showing some increase and one a small decrease in yields. The report did not attempt to quantify yield differences.

One study not included in the USDA report deserves special mention, however, because it controlled for variables other than the GT gene that

could affect yield. This research shows that when comparing several sets of GT and non-GT NI varieties, those with GT yielded about 5 percent less than conventional NI varieties (Elmore et al. 2001). The study concluded that the presence of the glyphosate tolerance gene was responsible for the yield reduction—an effect called yield drag. This work, conducted over a two-year period at several sites using several NI varieties and their counterparts, is probably among the best available for determining the effect of the GT gene on yield. Because special efforts were made to keep fields weed-free (hand weeding in addition to herbicides), these experiments do not necessarily reveal how different varieties of soybeans would respond to typical herbicide treatments on commercial farms.

Field trials conducted over a period of three years (1995–1997) in Tennessee used GT soybeans treated either with conventional herbicides or glyphosate (Roberts, Pendergrass, and Hayes 1999). These experiments would not account for the yield drag effects on GT soybeans noted by Elmore at al. (2001) because all varieties contain the GT gene, but these trials do compare the efficacy of different herbicide treatments. Seven of 11 non-GE herbicide combinations provided yields as high as glyphosate. All of the better-performing combinations of conventional herbicides are widely available. The authors note that higher infestations of grass weeds than those observed in their trials may reduce yields where non-glyphosate herbicides are used. On the other hand, shifts to more GT weeds and the development of glyphosate-resistant weeds could reduce the efficacy of glyphosate.

Over the past eight years, several weed species have developed resistance to glyphosate due to the overuse of this herbicide on GE crops, and these weeds now infest several million acres of farmland (International Survey of Herbicide Resistant Weeds 2009). Control of glyphosate-resistant weeds requires the use of different herbicides, while glyphosate may continue to be used to control weeds that remain susceptible. The emergence of

glyphosate-resistant weeds therefore may be eroding the convenience and efficacy of GT soybeans, as well as contributing to increased herbicide use.

In a summary of several hundred field trials, Raymer and Grey (2003) found that in the mid-1990s, on average, non-GT varieties and herbicide treatments out-yielded GT varieties where glyphosate was used. These yield differences appeared to be less in later field trials, suggesting that they were due at least in part to variety differences, including lower disease resistance, that were diminishing. The authors suggest that these trends may make GT varieties competitive in yield with non-GT varieties over time.

Overall, studies have reported both increases and decreases in yield of GT compared to non-GT soybeans, but the best-controlled studies suggest that GT has not increased—and may even have decreased—soybean yield. This is not necessarily surprising. The typical pesticide regimes and combinations of several herbicides used prior to the introduction of GT soybeans were generally effective, if inconvenient, in controlling weeds. Glyphosate has been effective against many species of weeds, and therefore more convenient because farmers can often avoid using several different herbicides and spraying schedules, but it does not necessarily provide better weed control than several other herbicides combined.

Recently, Monsanto Co. announced the release of a new GT soybean, called Roundup Ready 2 Yield (RR2Y), that is claimed to increase yield by 7–11 percent over previous GT soybeans. Significantly, increased yield is the result of insertion of the gene for glyphosate tolerance in a way that avoids the negative yield effect of the original GT soybeans, and the use of a soybean variety that provides high yield due to conventional breeding methods (Meyer et al. 2006). GE in this case does not increase yields, but merely eliminates the previous yield reduction associated with the original HT-engineered soybeans, such as was observed by Elmore et al. (2001).

Herbicide-Tolerant Corn: Operational Yield in the Presence of Weeds

Farmers have adopted transgenic HT varieties of corn more slowly than soybeans. This is probably due to the availability of effective herbicides, including ones to which corn is naturally tolerant. In the past six years, however, adoption of HT corn has greatly increased, reaching 63 percent of the corn crop in 2008 (Economic Research Service 2008b).

Switching to glyphosate from other systems might be of short-lived benefit, however, if measures are not taken to prevent the rise in glyphosate-resistant weeds. Several important corn weeds have already developed such resistance in several parts of the country because of the overuse of glyphosate in GT soybeans and cotton. These weeds include Palmer's amaranth (*Amaranthus palmeri*), ragweeds (*Ambrosia subspecies*), and johnsongrass (*Sorghum halapense*) (International Survey of Herbicide Resistant Weeds 2009). Another important weed of corn, goosegrass (*Eleusine indica*), has developed resistance to glyphosate outside the United States.

Several recent studies have compared yields achieved by transgenic and conventional corn-herbicide systems. In tests in North Carolina, all systems, conventional or transgenic, produced statistically equivalent yields if they incorporated post-crop-emergence herbicide applications, usually spread over the crop (Burke et al. 2008). None of the tested systems used atrazine, an herbicide with a controversial safety profile. Although more effective or less effective in controlling different individual weed species, combinations of herbicides used in non-transgenic corn were as effective overall as herbicides used *with* transgenic corn. This research apparently did not use NI varieties to compare either glyphosate- or glufosinate-tolerant varieties, so the possibility that differences in genetic background could have had an effect cannot be ruled out.

In other experiments carried out in North Carolina in 2004, all transgenic and non-transgenic

systems that incorporated over-the-crop application of herbicides provided high levels of weed control compared to herbicide applications applied in other ways, such as before crop emergence (Thomas et al. 2007). At several test sites, yields of the transgenic and non-transgenic corn varieties did not differ significantly, but overall the GT transgenic varieties produced the highest yields most often. The tested corn varieties were not near-isogenic, however, and the authors noted that yield differences may be explained by the genetics of the different varieties rather than by weed control.

Studies done in Kentucky at two locations over two years compared several non-transgenic herbicide systems and GT corn in tests that resulted in statistically equivalent weed control, although apparently using varieties that were not near-isogenic (Ferrell and Witt 2002). Glyphosate used with GT varieties provided better weed control than several of the herbicides used with non-transgenic corn but did not show statistically significant differences in yield. The authors noted that the low level of surviving weeds in the less effective non-GT systems was not sufficient to lower yield significantly. Similar results were found in research conducted over two years at two sites in Missouri and Illinois (Johnson et al. 2000).

In summary, based on the reviewed research, it does not appear that transgenic HT corn provides any consistent yield advantage over several non-transgenic herbicide systems. Transgenic corn generally achieves weed control equivalent to that of non-transgenic systems, but the weed control does not necessarily translate into higher yields. In some instances, when GT varieties produced a higher yield than did the non-transgenic systems, that yield advantage may have been the result of the different background genetics of the varieties used. As with other GE crops, motivations other than increased yield are more likely to be encouraging farmers to adopt HT corn.

Insect-Resistant Corn: Operational Yield in the Presence of Insects

Soil organisms produce a wide variety of *Bt* toxins that are effective against different types of insect pests. Corn varieties containing the gene *Cry1Ab* were first commercialized in the United States in 1996. This gene is mainly intended to control the larvae of a moth, the European corn borer (ECB, *Ostrinia nubilalis*), that damage the corn plant's leaves, bore into the stalks of corn, or attack the cob. The ECB can complete one to three generations during a growing season in different parts of the Corn Belt, with differences in impact between generations. The Southwestern corn borer, a problem in some areas, is also controlled by this variety of *Bt* corn. Several similar *Bt* genes have also been approved, including *Cry1F*, which in addition to controlling corn borers also provides some protection against several other insects—black cutworm (*Agrotis ipsilon*) and fall armyworm (*Spodoptera frugiperda*)—that are generally of less commercial importance. In 2004, corn containing a *Cry3Bb1* gene was introduced to control a different kind of corn pest, corn rootworm (*Diabrotica* species)—beetles whose larval stage damages corn roots—and a new *Bt*-based corn rootworm gene, *Cry34/35*, was recently approved by the U.S. Environmental Protection Agency.

Yield Effects of *Bt* Corn for Control of the European Corn Borer: Comparisons of *Bt* and Non-*Bt* Crops

Several research studies, which report yield data on a per-unit-area (e.g., per-acre) basis, provide a measure of the yield contribution of *Bt* transgenes to control of the corn borer. It is possible to use these data to estimate the overall impact of *Bt* transgenes on corn-crop yield at the national level. Such productivity information is invaluable in assessing the ability of *Bt* crops to contribute to food security on the international scale as well.

Field trials using NI varieties were conducted at several locations with differing levels of corn borer infestation. Dillehay and colleagues (2004) compared *Bt* and NI varieties over a period of

three years in Pennsylvania and Maryland, where ECB infestation levels varied from low to high. The non-*Bt* NI varieties that were not treated with insecticide to control ECB averaged 5.8 percent lower yield than the *Bt* varieties for all locations and dates. There were no yield differences between varieties when ECB levels were low, and there was no apparent yield lag for the *Bt* varieties compared to popular non-*Bt*, non-NI varieties.[6]

A three-year field trial in South Dakota compared several *Bt* corn varieties with NI non-*Bt* varieties, either treated twice with insecticide (permethrin)—for first- and second-generation ECB—or with no insecticide treatment for the NI variety (Catangui and Berg 2002). First- and second-generation ECB levels were high during one year (1997), and there was no significant difference in yield between the *Bt* varieties and the insecticide-treated non-*Bt* NI. Meanwhile, the *Bt* varieties had an 8 percent higher yield than untreated NI non-*Bt* varieties. For the two years when first-generation borer activity was very low and second-generation levels were moderate, there were no statistically significant differences in yield between varieties or treatments, including NI with no insecticide use. A three-year (2000–2002) study in Ottawa, Canada, using several pairs of *Bt* and NI varieties under low- to moderate-ECB levels, showed no significant differences in yields compared to no insecticide use (Ma and Subedi 2005).

Rice and Pilcher (1998) summarized 1997 results from 14 Iowa field trials, where *Bt* corn averaged 5 percent higher yields than NI varieties. At three locations in Minnesota in 1997, yield from *Bt* corn averaged 12 percent higher than yield from non-*Bt* NI varieties (Rice and Pilcher 1998).

Research performed in Wisconsin in 1995 and 1996 using *Bt* and corresponding NI varieties reported severe first-generation ECB infestation. The *Bt* varieties averaged about 7.5 percent higher yields than the NI varieties under standard farm-

ing practices (Lauer and Wedberg 1999).[7] In other research, infestation was relatively low in Indiana in 1994, and there was no significant difference in yield between *Bt* and NI varieties (Graeber, Nafziger, and Mies 1999). The non-*Bt* corn was treated with a microbial *Bt* for first- and second generation ECB, although microbial *Bt* is not recommended for treating second-generation ECB and is not the best available insecticide (Lauer and Wedberg 1999). Some of the crop was also artificially infested with large numbers of ECB larvae (60 larvae simulating each generation per plant). Only NI plants untreated with insecticide and artificially infested with both first- and second-generation larvae had lower yields, reduced by 6.6 percent, compared to *Bt* counterparts.

Yield data from crops raised prior to *Bt* corn's introduction can be useful in determining potential yield losses from ECB that are preventable by *Bt*. In 1991 an outbreak of ECB caused substantial losses in Minnesota and Iowa; the average loss for Minnesota was 14 bushels per acre (Rice and Ostlie 1997). This amounted to about a 12 percent yield loss (based on USDA corn-yield data for Minnesota in 1991), which could have been avoided had *Bt* corn been available.

In summary, when levels of ECB infestation are low or even moderate, most research reviewed here suggests that there is typically little or no significant yield difference between *Bt* varieties and their NI counterparts, even without insecticide treatment of the NI. When infestation levels are high, *Bt* corn provides yield advantages of about 7–12 percent compared to typical alternative practices used by conventional (non-organic) farmers.

The lack of yield advantage for *Bt* corn when there are low infestations of ECB contrasts with the often-cited report by the National Center for Agriculture Policy (NCFAP) (Gianessi, Sankula, and Reigner 2002), which estimated a substantial yield advantage for *Bt* corn on a state-by-state

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6   Some earlier studies reported yield lag—lower yield due to inferior background genetics—in some *Bt* varieties.
7   An extra case added artificial inoculation of first- and second-generation ECB to already high natural infestation levels. The *Bt* yields were 18 percent higher for this treatment. Its artificial nature and very high infestation levels, however, makes the relevance of these yield data difficult to interpret.

basis even at low levels of ECB infestation, but without providing supporting experimental data. Those estimates of yield loss at low ECB incidence ranged from zero to eight bushels per acre, averaging 4.4 bushels per acre (not weighted for corn acres per state). For some of the states considered by the NCFAP, field trial data have since been produced. For example, in Maryland and South Dakota, where the NCFAP estimated that low ECB infestations caused losses of eight and five bushels per acre, respectively, data from subsequent field trials showed no yield advantage for *Bt* corn when infestations were low (Dillehay et al. 2004; Catangui and Berg 2002).

By contrast, when ECB infestation levels are high, *Bt* varieties often provide higher yield than NI varieties, especially when the NI varieties are not treated with insecticides. Infestation levels alone are not predictive of yield loss, however, because pest damage is affected by environmental conditions and the stage of crop growth when the larvae are present. Therefore significant losses may sometimes occur even with low infestation levels, or minimal damage may occur with higher levels of infestation. Overall, the cited data suggest that when infestation levels are high, the yield advantage of the *Bt* gene is often about 10 percent compared to typical farmer practices used with non-*Bt* varieties. By comparison, Mitchell, Hurley, and Rice (2004) arrived at an average yield advantage of 2.8–6.6 percent on all *Bt* corn acres, based on modeling informed by field trial data for five states.

Although yield is the subject of this report, it must be noted that yield is not the only possible advantage of *Bt* corn. Reductions in chemical insecticide use through the substitution of *Bt* is generally considered to be beneficial to farm workers' health and the environment; this effect has been cited by farmers as being among the most important reasons to use *Bt* corn (Rice and Pilcher 1998).

National Yield Advantage: Aggregate Yield Attributable to *Bt* Corn Borer Corn

How do the yield data from individual experiments on *Bt* crops translate into impacts on nationwide corn yields? Estimating these impacts requires information on acres infested with ECB and the percentages of acres planted with *Bt* varieties or treated with insecticides. Such numbers are not easy to come by, first because ECB is an episodic pest that only emerges as a big problem every four to eight years and second because there have been two classes of *Bt* corn products on the market since 2004—one directed at corn borers and the other at rootworms.

One possible way to estimate the percentage of corn farmers that use *Bt* corn is to determine how many of them used insecticides to control ECB prior to the advent of *Bt* corn. But only a minority of U.S. farmers treated their corn to control ECB in a typical year. For example, despite an outbreak in Minnesota in 1991, just 5 percent of corn farmers used insecticides to control ECB despite substantial yield losses (Rice and Pilcher 1998). Surveys of farmers taken during the 1990s provide other measures of insecticide use. For example, studies done in 1995 by Rice and Ostlie (1997) found that during the year before the introduction of *Bt* corn, only about 28 percent of farmers in Iowa and Minnesota reported ever having used insecticide for ECB. This was in part because it was not economical to treat moderate infestation levels of ECB, given the limited effectiveness and cost of available insecticides. Because insecticides for ECB are used on only a small percentage of acres, yield differences between *Bt* corn and insecticide-treated non-*Bt* corn are a relatively minor factor overall.

More farmers use *Bt* corn than previously used insecticides because *Bt* corn may provide better ECB control. However, it is only economical for farmers to use the transgenic varieties when the value of added yield exceeds the additional cost of *Bt* seed; such eventualities occur primarily during years of heavy, and sometimes moderate, infestation. The need to make seed-purchasing decisions prior to the growing season, however, may increase the amount of *Bt* seed purchased. Because it is difficult

to accurately predict infestation and damage levels prior to growing the crop, many farmers buy *Bt* seed as "insurance" in case ECB reaches harmful levels.

Economically damaging outbreaks of ECB, based on insecticide efficacy and cost, typically occur in the upper Midwest—a primary corn-growing region—during only one year out of four to eight (Rice and Ostlie 1997), or between about 12 and 25 percent of growing seasons. But because of its greater efficacy, somewhat greater acreage may be economically justified for *Bt* corn, depending on the price of the seed.

Adoption of *Bt* corn reached about 26 percent by 1999, only three years after commercialization, but increased only an additional 6 percent the next five years, to a total of 32 percent (Economic Research Service 2008a). *Bt* corn directed at root-worm pests entered the market in 2004, and much of the increase in *Bt* corn acres since then is likely due to use of that class of products (Economic Research Service 2008c). Under current costs of *Bt* seed and prices for corn, it seems reasonable to estimate that about 30–35 percent of corn acres may be devoted to *Bt* corn for ECB or to stacked varieties that contain additional transgenes as well.

Yield data for *Bt* corn, compared to that of non-*Bt* corn produced from typical farm practices, can be used along with estimates of corn acreage infested with high and low levels of ECB to esti-mate national yield advantages for *Bt* corn. The published data are not extensive enough to arrive at precise yield data across years and regions of the United States (especially because the Southwestern corn borer can be a factor in some regions), but the data can still provide a rough estimate.

As noted above, *Bt* corn provides about a 7–12 percent yield advantage compared to non-*Bt* variet-ies for high ECB infestations and little or no yield advantage for most low- to moderate-infestation levels. Multiplying the acres infested with high or low levels of ECB by the corresponding typical *Bt* yield advantages, and then dividing by total corn acres, provides an estimated range of the total yield

advantage for ECB *Bt* corn. If about 12–25 percent of corn acres have high infestation levels on average (based on Rice and Ostlie 1997), then about 10-23 percent of *Bt* corn acres are planted where ECB infestation would otherwise be low to moderate.

A low estimate of *Bt* yield effects (assuming a 7 percent yield advantage on 12 percent of corn acres with high infestation) and no yield advan-tage on an additional 23 percent of *Bt* acres (aver-aged across all U.S. corn acres) results in a yield advantage of about 0.8 percent. A high estimate can be calculated by assuming a yield advantage of 12 percent on all *Bt* acres (that is, assuming high infestation levels on all *Bt* acres, and also assuming that about 33 percent of corn acres planted with *Bt* corn are aimed at the corn borer). In that case, *Bt* corn would provide about a 4.0 percent yield advantage averaged over all U.S. corn acres.

A more reasonable scenario is about a 10 per-cent yield advantage on 20 percent of *Bt* ECB corn acres (assuming heavy infestation once every five years) and a 2 percent advantage on another 15 percent of *Bt* acres (assuming a small yield advan-tage for light to moderate infestations), which gives a 2.3 percent yield advantage averaged over all U.S. corn acres. This estimate is in line with a calculation of 6.6 percent yield advantage for *Bt* in Iowa, using the highest estimate from the range of values of Mitchell, Hurley, and Rice (2004). When applied to all corn-growing states, and assuming 33 percent of acres devoted to *Bt* corn, this gives a 2.2 percent yield increase averaged over all corn acres.

Yield Effects of *Bt* Corn for Control of the Corn Rootworm

Aside from ECB, the other major insect pests of corn are species of corn rootworm, which col-lectively cause an estimated $1 billion in damages annually (Rice 2004). Rootworm larvae feed on corn roots, thereby reducing the uptake of water and nutrients and making the plants more sus-ceptible to toppling (lodging) in the fields. Adult beetles feed on corn tassels, but this does not usu-ally cause a substantial problem.

Several studies have examined the yield impacts of *Bt* corn aimed at rootworm control. As with ECB, current data do not allow a precise determination of yield benefit from the *Bt* gene, but they are sufficient for ballpark estimates. National yield impact is considered here as well as yield per unit area. The latter is important to individual farmers, who need to maximize production on the limited acreage under their control, while the national data provide an assessment of the impact of *Bt* corn for rootworm on the overall productivity of the corn crop.

A complication when considering rootworm is that some populations of Northern and Western corn rootworm have adapted to the corn-soybean biennial crop rotations common in the Midwest. Until the 1990s, damage from rootworm could be avoided by alternating the planting of corn and another crop—in particular, soybeans. Rootworm beetles laid their eggs in corn during the fall, but they did not lay many eggs in soybeans. Corn following soybeans thus had few rootworms, and any eggs laid after the corn harvest would hatch in soybean fields, where the larvae could not survive. Rootworm was a problem only where corn followed corn. But over the past two decades, some corn rootworms have developed ways to evade this form of cultural control. For example, some Western corn rootworms now lay eggs in soybeans (or other rotation crops), and they hatch the following year into corn. In areas where these rootworms are found, especially parts of Illinois and Indiana, corn-soy rotations no longer adequately prevent rootworm damage. Another type of adaptation allows eggs laid in corn to hatch in the corn crop that follows the intervening soybean crop. In this report, such pests are collectively referred to as rotation-adapted rootworms.

There are fewer published data on the yield impact of *Bt* corn for rootworm than for ECB. One widely cited study on the benefits of *Bt* rootworm corn cites modeling data based on an index that correlates root damage with yield loss (Mitchell, Hurley, and Rice 2004; Rice 2004;

Mitchell 2002). Yield advantage for *Bt* rootworm corn compared to insecticide use was estimated on average to be about 1.5-4.5 percent.

Iowa State University has been conducting field experiments comparing *Bt* rootworm varieties with either untreated NI controls or NIs treated with various insecticides. These insecticides include organophosphates, carbamates, and synthetic pyrethroids, which can cause considerable harm to the environment and human health. The experimental plots are located in different parts of Iowa, and they often use corn as a trap crop in years prior to the test in order to increase rootworm populations. Rootworm infestations are typically moderate to high, with damage to untreated controls often high to severe.

When feeding damage is low to moderate, several of the insecticide treatments typically perform as well as the *Bt* variety. But when damage in the untreated controls is high, *Bt* corn can show a significant yield advantage, although this result in not consistent across tests. For example, at a 2008 test site comparing many different *Bt* rootworm varieties and various insecticide-treatment plots, there was no significant yield difference between insecticide treatments and *Bt* crops. At Sutherland, Iowa, the single *Bt* rootworm variety that did not receive an insecticide application (most were treated with insecticide despite containing *Bt*) yielded about 3 percent more than the non-*Bt* NIs treated with insecticide (Gassmann and Weber 2008). In 2006, there were no statistically significant yield differences between *Bt* rootworm corn and insecticide treatments at several sites (Tollefson 2006) though at one site with a number of different insecticide treatments one *Bt* variety averaged 11 percent higher yield than the next five best insecticide treatments.

In 2005, rootworm injury and crop loss was often severe on untreated controls, and *Bt* corn provided significantly higher yields than insecticide treatments (Tollefson and Oleson 2005). The authors note, for example, a 30-bushel or greater benefit from *Bt* rootworm varieties compared to insecticide—a yield advantage of at least

14 percent. At a site experiencing serious drought, the yield advantage was at least 69 percent.

In sum, these tests suggest that *Bt* rootworm corn can provide substantially higher yields than insecticides under very high rootworm pressures and especially under unfavorable weather conditions. But the effect is not consistent, and in many tests insecticides performed about as well as *Bt* corn.

Several experiments in 2006 (Tollefson 2006) tested whether a variety of *Bt* rootworm corn and the NI variety had the same yield when there was no pest pressure—a test of whether the yield potential was, as would be expected, the same for the *Bt* and NI varieties. Surprisingly, the data showed that the *Bt* variety had a significantly higher yield—by about 8 percent. This result suggests that the tested *Bt* rootworm variety had a genetic yield advantage compared to its NI control. Such a bias may help account for some observed difference in tests. For example, subtracting 8 percent from the 11 or 14 percent yield advantages noted above leaves a 3–6 percent yield advantage for the transgene. As with any single study showing a new finding, additional studies should be performed to confirm it.

National Yield Advantage: Aggregate Yield Attributable to *Bt* Rootworm Corn

Although the yield differences between *Bt* corn and the better insecticide treatments tested in Iowa were generally positive, it is difficult to arrive at typical yield difference. While in some cases they were in the range of 10–20 percent for *Bt* rootworm corn (or even higher when drought occurred), in others there was no significant difference. We therefore use the estimate of Mitchell (2002) to determine national average yield gains for *Bt* rootworm corn compared to insecticide—about 1.5–4.5 percent—which takes a range of conditions into account.

National *Bt* corn usage data (Economic Research Service 2008a; Economic Research Service 2008c) suggest that if ECB *Bt* corn acreage

is about 33 percent, then most of the rest of the 57 percent of corn acres using *Bt* varieties are for rootworm, or 24 percent. In addition, *Bt* rootworm gene is found in stacked varieties that contain several transgenes. Estimates of insecticide use for controlling rootworms prior to *Bt* corn vary from about 13.3 million to 25 million acres (Rice 2004), or about 15–33 percent of corn acres (depending on acres planted, which varies by year). Using the yield advantage data of 1.5–4.5 percent, assuming that 33 percent of corn contains *Bt* rootworm varieties (at the high end of estimated treated corn acres), and averaging over the entire corn crop, the national yield advantage for *Bt* rootworm corn is about 0.5–1.5 percent. An average value, using 24 percent of acres planted with *Bt* rootworm varieties, gives about 0.4–1.1 percent yield advantage.

National Aggregate Yield Advantage of *Bt* Rootworm and *Bt* Corn Borer Corn

An estimate of the yield advantage provided by all *Bt* corn currently grown in the United States combines the yield advantages of ECB and rootworm *Bt* varieties taken separately. A low estimate, using the ECB yield advantage of 0.8 percent combined with the rootworm yield advantage of 0.5 percent, amounts to a total yield advantage of 1.3 percent. At the upper end, a 4.0 percent yield advantage for ECB added to a 1.5 percent yield advantage for rootworm gives a 5.5 percent yield advantage for the national corn crop. A 2.3 percent yield advantage for ECB is probably more realistic (see p. 20), which, added to the mean for rootworm of about 1 percent, gives an estimate of 3.3 percent.[8] Because of the uncertainties, a 3–4 percent yield advantage for *Bt* corn is probably reasonable.

It is relevant to ask whether the acreage planted with *Bt* corn may increase in the future. *Bt* corn for ECB may be near a roughly constant percentage of the crop, depending on economic factors and infestation levels. Earlier in the decade, the USDA suggested a leveling of demand at about

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8   The apparent "yield boost" of 1.65 percent (Mitchell et al. 2004), independent of ECB control, is not included in our yield estimates because, as acknowledged by the authors, some or all of it may be due to factors other than *Bt*. For example, it may result in part from continued breeding of the Bt varieties. If included, this factor would add about a 0.55 percent yield increase to our estimates.

25 percent of acres planted with ECB *Bt* varieties (Fernandez-Cornejo and McBride 2002). Although this estimate was not projected past 2002, barring significant changes in some of the underlying parameters these numbers may remain reasonable for a number of years to come. Mitchell and others found that in addition to ECB control, *Bt* corn for ECB provided a 1.65 percent "yield boost" of unknown cause (Mitchell, Hurley, and Rice 2004), which may partly explain an adoption rate— around 35 percent—somewhat higher than what was predicted by the USDA. Given these considerations, a substantial increase in the percentage of ECB *Bt* acres beyond current levels is not expected.

The amount of future corn acreage planted with *Bt* rootworm varieties depends in part on the spread of rotation-adapted rootworm variants that defeat the beneficial effects of the corn-soybean rotation, and in part on the use of alternative strategies where these rootworms already exist.[9] Onstad et al. (2003b) determined that further evolution of rotation-resistant variant Western corn rootworm could be halted, even assuming a dominant allele (a variant of a gene) for rotation adaptation, by widely planting three-year rotations that include wheat preceding corn. Because of the currently lower profitability of wheat, however, this scenario may not be economically feasible. Other modeling suggests that landscape diversity (land not planted with corn or rotated soybeans) could slow the spread of rotation-resistant rootworm (Onstad et al. 2003a). We therefore use current acres for rootworm *Bt* corn, with the understanding that if two-crop rotations continue to dominate in the Corn Belt, this acreage could increase.

Other Transgenes for Increased Yield: Field Trials of Experimental Genes

All crops containing transgenes are tested in field trials, usually for several years, before being approved for commercialization. Comparison of the number of field trials of transgenes intended to increase yield with the number of commercially successful yield-enhancing transgenic crops therefore provides another, albeit rough, measure of the degree of GE's success at realizing this goal. Meanwhile, the total number of these field trials suggests the accompanying level of effort to increase yield.

Since 1987, all field trials in which GE plants were to be propagated have required approval from the USDA. A publicly available record of approved field trial applications (Animal and Plant Health Inspection Service 2008) provides data on the genes, traits, and crops that have been investigated for the past 21 years.

Several limitations in the field trial database should be noted. First, the identities of a large percentage of genes are not revealed because the GE crop developer has claimed the gene as confidential business information (CBI). Although this practice greatly reduces the public's ability to identify the genes under investigation, the alternative used in this report entails examination of the phenotypes, or traits, expected in the engineered crops, which tend to be disclosed in the database. This approach does not allow an accurate determination of the number of different genes intended to increase yield; a particular gene is often used in several field trials, including in multiple crops and by multiple institutions, while other field trials include several different genes for a single phenotype. Nevertheless, the approach does establish the magnitude of genes that have been tested for yield improvement.

In general, we assume that genes intended to provide pest resistance or abiotic tolerance are also intended to increase yield rather than, for example, simply reduce costs, although this is not always the case. For genes that are intended to increase yield potential, as opposed to operational yield, the purpose of the genes is rarely ambiguous.

We also note that several phenotype categories listed by the USDA may sometimes be intended to increase yields but primarily serve other purposes. For example, genes for nitrogen-use efficiency or nitrogen uptake may increase yield for a given amount of applied nitrogen fertilizer, but their primary mission is to reduce the need for applied nitrogen. Such categories are not included in the discussion below.

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9   Agro-ecological principles suggest that two-crop rotations are rarely sufficient for pest control.

Table 1 shows the numbers of field-tested traits in categories typically intended to increase yields. The two categories from which crops have been successfully commercialized—insect resistance and HT—are listed separately. The intention here is to examine as-yet-uncommercialized genes. In particular, it should be noted that many insect resistance genes other than *Bt* have been tested, none of which have been commercialized. For example, there have been 15 non-*Bt* field trials for several genes intended to impart resistance to aphids. Excluding all HT and insect resistance genes therefore underestimates the number of operational-yield genes.

The table lists 1,787 field trials for resistance to plant pathogens (bacterial, fungal, viral, and nematode-related), including numerous genes. So far, only about five of these genes have been used commercially—virus resistance in papaya, squash (three genes), and plums—and comprise less than 1 percent of total GE acres. Only the gene for resistance to papaya ringspot virus can be considered a commercial success, and so far it has been used only in Hawaii.

None of the other categories has produced any commercial successes. Although there have been 583 field trials for abiotic stress tolerance—phenotypes include cold, heat, drought, shade, salt, and metal tolerances, among others—none of these genes have been used commercially.

There have been 652 field trials with yield listed in the database as the phenotype. Most of them were likely aimed at intrinsic-yield increase, and none of these transgenic crops have yet been commercialized.

In summary, beyond the category of virus resistance (for a very few virus-tolerant traits), none of the 3,022 field trials—which do not include HT and insect resistance—have led to commercialized varieties with significant impact on national yield. Virus-resistant papaya, however, has helped conventional farmers in Hawaii continue growing that crop.

The very low percentage of commercial transgenes for increased yield raises the question of why more of these transgenes have not been successful. No study that we are aware of has tried to answer this question, and therefore we consider several possibilities.

A trivial answer is that sometimes the field trials were not intended to lead to commercialization. This may have been the case if the gene was being used only for basic research, such as in trying to

Table 1. Field Trials of Genetically Engineered Crops Having Traits Associated with Increased Yield

Transgenic Trait	Number of Approved Field Trials, 1987–1999	Number of Approved Field Trials, 1987–2008
Bacterial Resistance	70	139
Fungal Resistance	301	713
Nematode Resistance	6	51
Virus Resistance	635	884
Herbicide Tolerance (HT)	1,729	4,623
Insect Resistance (IR)	1,487	3,630
Abiotic Stress Tolerance	41	583
Yield	55	652
Totals	4,324 (1,108)	11,275 (3,022)

Note: Numbers in parentheses indicate field trial numbers minus HT and IR.

Source: Data from Animal and Plant Health Inspection Service 2008.

understand how the gene functions in the plant, or in the few field trials using non-crop research species such as *Arabidopsis*. This explanation is likely to apply, however, only to a small minority of the field trials included in Table 1. Most field trials, about 82 percent, were conducted by companies or other entities that were motivated primarily by commercialization of the transgenic crop, with almost all of the rest conducted by universities.[10] And because companies and universities alike have strong interests in eventual commercialization, only a small percentage of the field trials included in Table 1 were conducted without that goal.

Some of these transgenes may simply not be ready for commercialization. It typically takes several years of field trials and safety testing to acquire enough data about the crop, both for safety purposes and to make sure it performs as intended, before a transgenic crop is approved. However, as seen in Table 1, 1,108 of these field trials—not including those aimed at herbicide tolerance or insect resistance—were approved prior to 2000. Most of these earlier transgenic crops could have been ready for commercialization by the time of this report, but none have been submitted to the USDA for approval as of February 2009.

One possible reason for the lack of commercialization of some GE crops may be insufficient consumer acceptance. This would be especially true for food crops. But the field trial record includes numerous experimental yield-enhancing genes of a subset of transgenic crops that have already been widely commercialized—canola, corn, cotton, and soybeans—and thus it is unlikely that these genes' lack of commercialization was caused by consumer rejection.

The most likely explanation for many of the failures to achieve commercial success are: (1) technical challenges inherent in the unpredictable interaction of transgenes in the imperfectly understood genetic environment of the crop; or (2) limited knowledge of the new trait's efficacy prior to growing the transgenic crop in the field. Unpredicted properties of the transgene may result in deleterious unintended side effects, common in transgenic crops, that could reduce their agronomic performance or safety. For example, *Bt* corn varieties containing *Cry1Ab* genes have been reported to have elevated levels of lignin (a structural component of stems) compared to NI non-*Bt* varieties (Poerschmann et al. 2005)—an unexpected and poorly understood result. Some of these side effects may have little agronomic or safety impact, but others may make the transgenic crop unmarketable or unsafe.

Whatever the reasons, the record of GE has not kept pace with yield increases accomplished by other means, such as traditional breeding or newer methods that enhance selective breeding with molecular-marker technology such as marker-assisted selection. As noted earlier, corn yield has been increasing on average by about 1 percent per year over the past several decades.

Looking at yield increases more closely with the aid of the USDA national data, we find that the contribution of GE continues to be greatly overshadowed by other methods. Average yields for the five years prior to the introduction of GE crops, 1991–1995, can be compared to the yields of the five most recent years of 2004–2008.[11] Corn, soybeans, and wheat averaged 118.6, 36.2, and 37 bushels per acre, respectively, during the earlier five years and 152.4, 41.9, and 41.8 during 2004–2008. These changes amounted to yield increases of 28 percent for corn, 16 percent for soybeans, and 13 percent for wheat. A 4 percent yield enhancement from *Bt* corn accounted for about 14 percent of the increase in corn yields over the past 14 years. And GE has not contributed to the yield increases that have occurred in soybeans, wheat, and other crops.

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10 Based on USDA data (Animal and Plant Health Inspection Service 2008), 13,909 field trials were approved between 1987 and January 5, 2009, for companies, universities, and other organizations, with 2,518 of those for universities and nonprofit organizations. Thus 81.9 percent of the trials were approved for commercial entities (there are very few field trials conducted by other types of organizations).

11 HT soybeans were introduced in 1995, but they represented only a small percentage of acres that year. Five-year averages are used because they reduce the otherwise large variability of yields from year to year. However, even five-year averages are only a rough approximation of yield change, because factors that can greatly affect yield may still vary considerably between five-year periods.

CHAPTER 4

Alternatives to Genetic Engineering for Insect Resistance and Herbicide Tolerance

GE crops are not the only alternative to the U.S. agricultural practices predominantly used for controlling corn borers, rootworms, and weeds. Other methods of growing crops may provide benefits when compared to those of current industrial high-input agricultural production, and at the same time produce comparable yields. They include organic agriculture (pursued, for example, in accordance with the USDA standards) and "low-external-input" (LEI) methods that apply agro-ecological principles to control pests.[12] Conventional crop breeding may provide additional possibilities, especially for resistance to insects.

Because organic and many tested LEI systems do not use transgenic crops, they could provide a good alternative for comparison to transgenics. There have been very few studies, however, that have directly examined the efficacy of these systems for controlling pests that are the target of *Bt* genes. For example, while recent experiments in the Midwest often produced yields of organically grown corn and soybeans 90–114 percent that of conventional systems, these experiments did not use transgenic varieties for direct comparison (Posner et al. 2008; Delate and Cambardella 2004; Delate et al. 2003). The experiments were conducted in areas that often experience corn borer and rootworm damage, but only one experiment assessed corn borer impacts (Delate and Cambardella 2004), though with levels of ECB too low to cause economic yield reductions in either

organic or conventional plots. In South Dakota experiments, organic corn yields were about 16 percent lower than, and organic wheat and soybean yields were comparable to, those of conventionally grown counterparts (Smolik, Dobbs, and Rickert 1995). Subsequent experiments in South Dakota produced comparable corn yields but 30 percent lower soybean yields (Dobbs and Smolik 1996).

A 21-year study in Pennsylvania compared several organic production systems, which used either animal manure or legumes to supply nitrogen, with conventional corn and soybeans. Organic corn yields were equivalent to conventional yields, and soybean yields averaged about 7 percent less (Pimentel et al. 2005). Over five drought years, organic corn yielded 28–34 percent more than conventional corn, although in a later severe drought year the conventional corn yielded 2.6 times more than the legume-based organic system but 37 percent less than the manure-based system. Organic soybeans averaged yields that were 78 percent higher than conventional soybeans during the severe drought year of 1999.

Where yields have been lower in organic systems than in conventional corn and soybeans, inadequate weed control in the organic system has often been responsible (Posner et al. 2008), with yields in one experiment only 66 percent that of the conventional crop. Despite this single year of low yields, average yields over five to eight years were 90 percent of conventional yields (Posner et al. 2008). Research in Europe suggests that

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[12] LEI systems, like organic, attempt to achieve high production while promoting sustainability and substantial ecosystem services. Unlike organic systems, LEI allows modest input of synthetic chemicals.

inadequate soil nutrients, especially nitrogen and phosphorus, may substantially reduce organic yields (Mader et al. 2002), but a recent analysis indicates that adequate nitrogen may be achievable in organic systems (Badgley et al. 2007).

In one greenhouse study, significantly fewer corn borer eggs were laid in corn grown in organic soils than in soils of conventional fields (Phelan, Mason, and Stinner 1995), suggesting that organically grown corn may harbor fewer ECB larvae than conventionally grown corn.

Research with LEI systems has shown mixed results for yield in comparison with conventional systems, though recent work in Iowa over three years demonstrated the ability of some LEI systems to produce higher yields. In the last year, which used glyphosate-tolerant soybeans in the conventional system (Liebman et al. 2008), the LEI system produced soybean yields that were 13 percent higher. The LEI system used 76 and 83 percent less herbicide than the conventional system for three- and four-year crop rotations, respectively.

A particular challenge is presented by rootworms adapted to crop rotation, a common practice both in organic and LEI systems.[13] Wheat does not attract as much egg-laying by rotation-adapted rootworms as do other tested crops, nor is there as much damage to corn planted the following season (Schroeder, Ratcliffe, and Gray 2005). In some cases, the lower levels of egg-laying in wheat preceding corn may be sufficient to prevent economically significant yield reductions.

Landscape-level control may also reduce yield loss by rotation-resistant rootworm. Evidence from population genetics and modeling (Onstad et al. 2003a) strongly suggests that plant diversity at the landscape level would slow the spread of rootworm types that are adapted to the corn-soybean rotation. As mentioned earlier, three or more crop rotations would challenge even the rotation-resistant rootworm, as most larvae would not survive in the non-corn crop that would be present during most years. Three-year rotations may not be sufficient, however, where rotation-adapted rootworm is already predominant, but the published work has not explored rotations longer than three years. Recent simulations suggest that long rotations in the Midwest could be highly productive and often more profitable than the current corn/soy rotation, especially if current misguided commodity-crop subsidies did not discourage the planting of forage crops such as alfalfa. But this work did not specifically address corn rootworm (Olmstead and Brummer 2008).

Finally, the potential of conventional breeding approaches has not been exhausted. Traditional breeders have already achieved substantial first-generation corn borer resistance, but it has been associated with yield drag (yield reduction associated with a trait as an unintended side effect) compared to more susceptible genotypes. Resistance to second-generation corn borer has not been commercially available because it is more difficult to achieve. However, recent work, especially with tropical corn varieties, has shown some promise for developing both first- and second-generation corn borer resistance (Flint-Garcia, Darrah, and McMullen 2003), although more research is needed to determine how much protection they may confer. Marker-assisted selection, using genomic markers to track traits during breeding, shows promise for achieving some measure of second-generation ECB resistance.

New soybean varieties expected for 2009, projected to increase yield an average of 5 percent, were developed using advanced conventional breeding methods rather than GE (Perkins 2008).

In summary, several approaches other than current pesticide regimes and GE have the potential to reduce yield loss from weeds, corn borer, and rootworm in soybeans and corn. These approaches often are also associated with other benefits as well, such as lower levels of pesticide use, improved soil, carbon sequestration, and improved water quality.

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[13] Although rotation-adapted rootworms arose from the corn/soybean rotation predominant in conventional agriculture, these rootworms may also cause damage in longer rotations, often used in organic and LEI systems, when they lay their eggs in the crop preceding corn.

CHAPTER 5

Can Genetic Engineering Increase Food Production in the Twenty-first Century?

This chapter examines the promise of the next generation of GE traits to improve crop productivity, and it highlights some of the accompanying challenges. The focus is primarily on genes for increased *potential* yield, but the issues explored also apply to traits for increasing *operational* yield. It must be noted, however, that many of the genes now being considered for increasing yield involve greater genetic, biochemical, and phenotypic complexity than current genes for insect resistance or herbicide tolerance, and this complexity will sometimes exacerbate the tendency of GE to produce side effects, some of which may be unacceptable. We also discuss several genes for increasing yield potential that have been mentioned in the science literature, along with recent research suggesting theoretical limits on yield.

The technology to screen and identify new genes of interest is advancing, and as a result a substantial effort to develop GE traits for improving crop productivity is under way. As can be seen in Table 1, the numbers of experimental field trials for abiotic stress-related traits and yield-potential genes have increased dramatically in the past nine years, about 13-fold and 11-fold, respectively—far greater than for other genetically engineered traits.[14] This suggests that the industry is finding many more prospective genes for yield and abiotic stress tolerance than in earlier years.

Theoretical Considerations

In general, potential yield may be raised by improving the efficiency of photosynthesis, improving the efficiency of resource use by the plant, or enlarging resource allocations to the food/feed components of the crop, all of which have been targets of research for many years. But to understand the potential for increasing yield, it is useful to consider some of its physical and physiological limits.

Several reviewers have noted that despite identification of promising traits for intrinsic yield in the past, there has been little success in translating that knowledge into actual increases in agricultural production (Sinclair, Purcell, and Sneller 2004; Miflin 2000). One general difficulty is that many improvements have been aimed at aspects of plant physiology that are several steps removed from grain yield. Improving the efficiency of photosynthesis, for example, may not translate into substantial yield improvements because several intervening biochemical and physiological steps may each reduce the amount of captured light energy that is transferred to the next step (Sinclair, Purcell, and Sneller 2004).

Another barrier to practical results is the complexity of genes involved with yield potential. They are often parts of genetic networks that have multiple and far-reaching effects on the growth or development of the plant. By contrast, *Bt* and HT genes and their protein products generally have fewer interactions with the plant genome or physiology.[15]

One example of the potential problems caused by multiple phenotypes can be seen with the gene *ADP-glucose pyrophosphorylase* (*ADP-GP*). This gene has been used in at least 23 experimental field

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14 It should be noted, however, that in terms of quantity, field trials for insect resistance and herbicide tolerance still far outnumber those for yield, abiotic stress, and other traits.

15 *Bt* transgenes produce insect-toxic proteins that are not known to participate in any plant metabolic pathway other than what is needed for their own production, for example, and the *CP4-EPSPS* gene for glyphosate tolerance substitutes for a similar plant gene in an amino acid synthesis pathway.

trials since 1993 aimed at increasing yield (Animal and Plant Health Inspection Service 2008).[16] Plants containing versions of this gene raised seed yield substantially, about 11–18 percent for corn and 38 percent for wheat (Giroux et al. 1996; Smidanski et al. 2002). Another result of enhanced *ADP-GP* activity, however, is the overall increase in plant size, about 31 percent for wheat. Because of the limits to plant biomass in a field, and of inter-plant shading effects, it is unclear how much the yield per isolated plant may actually translate into yield on the farm. In addition, the possible overall increase in biomass may require larger inputs of fertilizer, which could exacerbate problems related to pollution and energy use.

An optimistic view of the potential for increased photosynthesis to substantially increase grain yield is presented by Long et al. (2006). The authors point out, based both on theory and practice, that because several target-gene products and traits involved with increasing the efficiency of photosynthesis show particular promise, their use may be able to increase yield as much as 50 percent for many crops over the next several decades.

Long and colleagues argue that fully exploiting most of the approaches to possible yield increases that they identify will require GE; the reason is that the photosynthetic enzymes with highest potential to increase yield are found in organisms that are not sexually compatible with most crops, thereby excluding breeding as an option. In addition, the authors believe that GE could achieve results much faster than conventional breeding methods. Long and colleagues do not discuss, however, how much genetic potential in the relevant photosynthesis genes may remain to be discovered within crop varieties themselves or in their sexually compatible wild relatives.

These authors also do not consider several aspects of the development of GE crops that

substantially lengthen the time required to achieve commercialization. First, a considerable amount of time-consuming breeding between the transgenic plants and conventional varieties is required for GE. Such breeding may also be needed to eliminate deleterious mutations in the engineered plant often caused by the GE process. Moreover, the regulatory process typically requires several years to complete, and field testing for several years is needed in order to test the performance of the transgenic crop under several environments and for environmental safety.

In addition, the potential for deleterious side effects of the transgene needs to be considered.[17] Beyond the *ADP-GP* example above, several other genes currently under study illustrate this potential problem. In general, many of the genes now being explored for increasing yield are each involved in the expression of several phenotypes or developmental pathways. Often, these genes are transcription factors that directly or indirectly regulate the expression of numerous other genes in response to environmental signals, at particular stages of development, or in particular plant tissues. Other yield-enhancing transgenes are parts of signal transduction pathways, transmitting information from the environment, development, or from other genes. And as with transcription factors, they typically affect the expression of many other genes in turn.

Examples of Genes for Increased Yield

Although it is not possible to positively identify the lead genes for major biotechnology companies because of CBI restrictions, several yield genes can be considered because they are in field-trial testing, patented, or reported in the research literature.

One widely researched transcription factor associated with yield is *APETALA2* (*AP2*), which was first recognized for its important role in flower development. Strong mutations (complete loss of

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16 This number of field trials for *ADP-GP* is a minimum because the names of most genes used by companies in field trials are not disclosed to the public, having been declared confidential business information (CBI). For example, one of the authors of Giroux et al. (1996) was an employee of Monsanto Co., so the company had some interest in this gene. Thus it is not disclosed in any of Monsanto's yield field trials, and it is not possible to know whether Monsanto actually used it.

17 Genes discussed by Long et al. (2006) mainly encode enzymes rather than the transcription factors and signal transduction proteins discussed below in the text. But pleiotropic effects (side effects whereby a single gene influences multiple phenotypic traits) are widely observed in genes for other proteins as well (Kuiper et al. 2001). Whether pleiotropic effects occur with these transgenic enzymes, and whether they are harmful, will require careful testing.

function) in this gene cause unacceptable alterations in flower form and function, but milder mutations that retain some function show yield advantages without severe developmental defects. These milder mutations can significantly increase seed size and total plant seed mass in some plant species (Jofuku et al. 2005; Ohto et al. 2005). Another side effect that has already been identified in a plant commonly used in research (*Arabidopsis*) is a 37–57 percent increase in the fatty acid called lignoceric acid and a corresponding 20–27 percent decrease in oleic acid (Jofuku et al. 2005).

In general, major side effects in plant form or function will be readily identified, but side effects that do not drastically alter the plant or that occur only under a subset of environmental conditions may go undetected, especially in the absence of considerable experimental effort and expense.

In addition to affecting seed and flower production, *AP2* is involved in the regulation of other important aspects of plant metabolism, such as the biochemical pathway involving the plant hormone ethylene—a basic part of plant response to stresses (both biotic and abiotic) as well as of fruit ripening. *AP2* mutants thus alter the expression of genes, including plant-disease defense genes that respond to ethylene (Ogawa, Uchimiya, and Kawai-Yamada 2007). The wide-ranging interconnections between *AP2* and other plant processes pose a challenge to detecting side effects that are not readily associated with seed size but that may be harmful under certain conditions.

Some of the many other genes that have been explored for their ability to increase yield and that have wide-ranging effects on plant metabolism include *fasciated ear2* (*fea2*) (Taguchi-Shiobara et al. 2001), which controls branching and seed number; *Phytochrome B* (Thiele et al. 1999), which regulates plant light responses; and CDK inhibitor-like proteins in corn (U.S. patent 7,329,799, assigned to Monsanto Co., issued February 12, 2008).

An example of a recently discussed drought-tolerance gene illustrates how some side effects may be only distantly connected to the engineered trait and therefore difficult to anticipate or discover. The *era1* transgene was touted in the popular press and scientific literature as showing substantial potential for increasing yield in wheat under drought conditions (Pollack 2008; Wang et al. 2005). A related gene, *fta*, and transgenic protein, which functions in conjunction with *era1*, have been shown to have similar properties (Wang et al. 2009). An important side effect that often accompanies drought tolerance—reduced yields under normal water availability—was not observed in wheat plants containing this gene, though nonfunctional mutants of these genes have other developmental side effects that are more obvious, such as outsized floral organs and delayed growth (Wang et al. 2009, Wang et al. 2005, Running et al. 2004).

An unanticipated side effect caused by the *era1* gene was recently discovered by other scientists. They found that it is also involved in resistance to several important types of plant pathogens (Goritschnig et al. 2008) through its ability to modify the activity of a number of proteins. Mutant versions of the gene, such as *ear1,* can make plants more susceptible to infection by these pathogens. There was no reason to believe *a priori* that a gene that conferred drought tolerance would be involved in disease resistance, so it is fortuitous that this side effect was discovered.

There are several ways to try to eliminate or reduce undesirable side effects. One method is to use gene regulators, called promoters, that restrict functioning of the gene to only those plant tissues, or in response to environmental conditions, in which gene function is desired. For *era1* and *fta* genes, promoters that enable gene function only under drought conditions or in the aboveground parts of the plant are used. Moderate drought for a limited period of time does not seem to cause the obvious developmental problems otherwise observed with *era1* and *fta* genes (Wang et al. 2009; Wang et al. 2005). This does not necessarily prevent important, though less obvious, side effects

during drought conditions. Therefore restricting *era1* function to drought conditions may address undesired side effects on flower form but may not address increased disease susceptibility during drought. And because disease incidence is usually sporadic, this side effect may not be detected during field trials.

A similar approach, one that uses seed-specific gene regulators, might be used with *AP2* genes to avoid dramatic side effects such as altered flower form. This approach, however, might not prevent side effects in the seed, which is of particular concern as the consumed part of the crop. In addition to affecting the seed itself in unpredictable ways, some complex side effects may be transmitted from the plant tissue where it originates to other parts of the plant (Cheong et al. 2002; Mittler 2002; McDowell and Dangl 2000).

CHAPTER 6

Conclusions and Recommendations

While crop GE has been hailed by some as critically important for ensuring adequate food supply in the future, it has so far produced only small increases in yields in the United States. Our review of available data on transgenic *Bt* corn, as well as on transgenic HT corn and soybeans, arrives at an estimated total yield benefit of about 3–4 percent for corn. Individual farmers may achieve substantially higher yields from *Bt* corn under certain circumstances, such as when corn borer infestations are high, and they may also use *Bt* corn to reduce exposure to chemical insecticides and for other reasons. But when considering the benefits to society as a whole, the contribution of *Bt* genes to overall yield in corn has been modest; it is also significant that the yield increases have been from *operational* yield—reduction in yield losses—rather than from the *intrinsic* yield of the crop. Moreover, there have been no apparent overall yield increases, operational or intrinsic, from HT corn and soybeans.

This record, compiled over the 13-year period since transgenic crops were first commercialized in the United States, compares unfavorably with the historical and current trends of major-crop yield enhancements that have been achieved by other means. For example, corn yields over the past several decades have increased an average of about 1 percent per year—considerably greater than the increase that can be attributed specifically to GE. Corn yields have increased about 28 percent since *Bt* corn was first planted commercially (as determined by comparing the average yield for the five years preceding the introduction of *Bt* corn with the average yield over the past five years). But the 4 percent yield enhancement contributed by *Bt*

varieties constitutes only about 14 percent of this overall corn yield increase, with 86 percent coming from other technologies or methods.

The failure of GE to increase intrinsic yield so far is especially important when considering food sufficiency. Substantial yield increases can be achieved through operational yield, and there is room for achieving huge operational yield increases in much of the developing world. But intrinsic yield sets a ceiling that is proving difficult to surpass. So far, the only technology with a proven record at increasing intrinsic yield is traditional breeding, which now includes genomic methods.

Although GE may have something to contribute to intrinsic yield in the future, it would be foolish to neglect proven breeding technologies while waiting to see if such possibilities materialize. Similarly, sustainable agro-ecological methods are already showing considerable promise for contributing to operational yield, especially in the developing world, where GE has had limited impact so far. It would be better to provide more resources for more promising technologies—traditional and marker-assisted breeding methods and agro-ecological approaches such as organic and low-external-input methods—which currently suffer from meager financial and research support. This does not mean that GE should be abandoned but rather that public resources be shifted to more propitious methods. Such a change in public policy is especially indicated for agro-ecological approaches, which, because they are knowledge-based rather than capital-intensive, are not usually attractive to large companies.

The lack of substantial yield increases has not been due to lack of effort. The several thousand

field trials over the last 20 years for genes aimed at increasing operational or intrinsic yield indicate a significant undertaking. Yet none of these field trials have resulted in increased yield in commercialized major food/feed crops, with the exception of small increases from *Bt* corn.

The modest past performance of GE crops in enhancing yield suggests caution when considering laudatory claims for the future, although it is always possible that advances in transgenic technology may ultimately produce better results. Still, when evaluating the potential of GE crops to increase yields in coming years, an important factor to consider is that many genes under consideration for yield enhancement have multiple effects on plant phenotypes and development, unlike the relatively straightforward effects of currently commercialized genes. Perhaps most challenging will be avoiding the potentially numerous harmful side effects that may be associated with many of these genes.

Given the tremendous resources being devoted to developing yield-enhancing and other new transgenic crops (as reflected in the considerable increase in field trials aimed at improved yield), it would not be surprising if some of them succeed. It is therefore important to consider the contribution and potential of GE compared to other technologies and methods, such as organic and low-external-input methods, which not only show promise for increasing yield but also provide other significant benefits. These benefits include better soil moisture retention (which improves crop performance during drought), reduced water pollution, and boosts to rural economies and farmers. Putting too many of our crop-development eggs in the GE basket, thereby depriving these other methods of adequate resources, could lead to lost opportunities for improving yields and enhancing other critical aspects of a healthy agriculture.

In order to better ensure that major crops have adequate yields in the coming years, the Union of Concerned Scientists makes the following recommendations:

- Public discourse on GE should carefully distinguish between operational yield and intrinsic yield, noting that GE crops to date have not contributed traits that would increase the latter.

- The U.S. Department of Agriculture, state and local agricultural agencies, and public and private universities should redirect substantial funding, research, and incentives toward approaches that are proven and show more promise than genetic engineering for improving crop yields, especially intrinsic crop yields, and for providing other societal benefits. These approaches include modern methods of conventional plant breeding as well as organic and other sophisticated low-input farming practices.

- Food-aid organizations should work with farmers in developing countries, where increasing local levels of food production is an urgent priority, to make these more promising and affordable methods available.

- Relevant regulatory agencies should develop and implement techniques to better identify and evaluate potentially harmful side effects of the newer and more complex genetically engineered crops. These effects are likely to become more prevalent, and current regulations are too weak to detect them reliably and prevent them from occurring.

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Glossary

Abiotic: Descriptor of non-living environmental factors that affect the growth of crops. Abiotic stresses include drought, frost, floods, soils containing salts or heavy metals, shade, and heat.

Aggregate yield: In the context of this report, the total yield of a crop such as corn or soybeans in the United States.

Agro-ecology: The science of applying ecological principles to agriculture in order to maximize crop productivity while protecting environmental quality and sustainability. Agro-ecology typically includes **organic** and **low-external-input** production methods.

Anthropogenic: Attributable to human actions.

Biofuels: Energy sources, for transportation or other purposes, that are generated from organic matter—often, corn or other materials such as wood or grasses.

Biotechnology: Technology related to the manipulation of living organisms. Often used interchangeably with **genetic engineering** and genetic modification.

***Bt* crop:** A crop variety, engineered to contain a gene from the soil bacterium *Bacillus thuringiensis* that produces a toxin effective against one of several insect pests, including European corn borer and corn rootworm.

Commodity crops: Crops that are eligible to receive subsidies under Title I of the federal food and farm bill. Also called row crops, they include corn, wheat, rice, soybeans, and cotton.

Confidential business information (CBI): Corporate information that is not publicly available because disclosure would be seen as compromising its economic value to the developer.

Corn rootworm: A beetle whose larvae are a major destructive pest of corn in the United States. Several species of this insect are classified under the genus *Diabrotica*.

Crop rotation: The alternating of different crops—a practice that typically has multiple benefits, such as the reduction of pest damage and the improvement of soil quality. The minimum rotation consists of two crops, such as the prevalent corn/soybean rotation in the U.S. Midwest. These short rotations provide fewer benefits than longer rotations.

Dead zone: An area in water bodies—notably, the Gulf of Mexico—where oxygen levels are too low to support commercially valuable fish and other sea life. Dead zones are created when high levels of nitrogen nutrients are lost from fields and enter waterways, prompting microorganism populations to spike as they consume the nutrients. After the microorganisms die, the decaying process absorbs oxygen from the water.

European corn borer (ECB): A moth (*Ostrinia nubilalis*) whose larvae are one of the major insect pests of corn in the United States.

Genetic engineering (GE): A technology for inserting genes or regulatory sequences from one organism into the genome of another, thereby allowing the acquired gene to be passed to progeny through reproduction. The two major categories of

GE crops are those that are engineered for insect resistance (corn and cotton containing *Bt* genes) and herbicide tolerance (corn, cotton, canola, and soybeans containing genes that allow them to withstand herbicide applications).

Glyphosate: An herbicide that is effective against many species of weeds. Over 90 percent of all U.S. soybeans are engineered to tolerate glyphosate (a popular brand being Roundup).

Inputs: In the context of this report, substances that are needed to produce crops. Examples include fertilizers, seeds, irrigation, and pesticides.

Intrinsic yield: The highest yield, or production level, that a crop variety may achieve under ideal conditions. Also referred to as **potential yield,** it is distinct from **operational yield**.

Low-external-input (LEI): A farming method that applies agro-ecological principles of timing, crop rotation, and integrated pest management, among others, to control pests and increase production. Unlike organic farming, however, minimal use of synthetic fertilizers and pesticides is allowed.

Marker-assisted selection: A breeding method that brings several desired genes, such as those for higher yield or drought tolerance, together in a crop by tracking molecular "barcodes" (markers) associated with those traits. This method often allows faster breeding, as well as the breeding of complex traits (such as yield) that consist of several genes.

Near-isogenic (NI): Refers to plant varieties that are nearly identical to each other genetically, except for a particular gene of interest (in this report, that gene is usually either a *Bt* or an herbicide-tolerance gene). This property permits evaluation of the transgene's contribution to yield or other traits.

Operational yield: Actual yield of a crop in real environments, after the damages from pests, abiotic stresses, inadequate inputs, and weather events have been taken into account. This term is distinct from **intrinsic yield** (which is also called **potential yield**).

Organic: Refers to a set of principles for cultivating crops that eschews genetically engineered crop varieties and synthetic fertilizers and pesticides. Organic operations use animal manure or legumes to supply fertilizer, often use **crop rotations** to foil pests, and grow cover crops to preserve and build soil quality. Organic operations contrast with conventional industrial systems.

Overall yield: Also called **aggregate yield**, this is the total yield of the crop—at the national level, for example—as opposed to the yield that an individual farmer may experience. The term is also distinct from the yield that may occur on a subset of the total crop (such as the yield of a particular field, measured on a per-acre basis).

Phenotype: The set of physically apparent traits in an organism, as opposed to its genotype, or set of genes. Relevant traits in the phenotype of a crop include yield, pest resistance, and drought tolerance.

Pleiotropic: Refers to the multiple effects of a gene, some of which may have agronomic or safety implications. Pleiotropic effects are common in **transgenic** crops because of the unpredictable interactions between the transgene or transgenic protein and the crop genome, but they may also occur in conventional crop breeding.

Potential yield: Yield of the crop when grown under ideal conditions, thereby representing the plant's intrinsic or peak productive capacity. Also referred to as **intrinsic yield**, it is distinct from **operational yield**.

Rotation-adapted rootworm: Corn rootworms that are no longer adequately controlled by corn/soybean crop rotations. There are two recognized types—often called variant corn rootworm and extended diapause corn rootworm—but these are not usually distinguished in this report.

Stacked: Descriptor of genetically engineered crop varieties that contain more than one transgene.

Sustainable agriculture: A set of principles for cultivating crops and raising livestock that safeguards environmental quality to ensure continued productive capacity in the future.

Transgenic: Refers to organisms containing genes that have been inserted into their genetic code, usually from other organisms (transgenes), using methods that isolate the transgene from other genes of the donor organism in the laboratory.

Yield: Productivity of farmland, measured in units of harvested crop per unit of land in a specified amount of time. See also **aggregate yield**, **intrinsic yield**, **operational yield**, **overall yield**, and **potential yield**.

Yield drag: Yield reduction that occurs as an unintended side effect of a given trait.

FAILURE TO YIELD

Evaluating the Performance of Genetically Engineered Crops
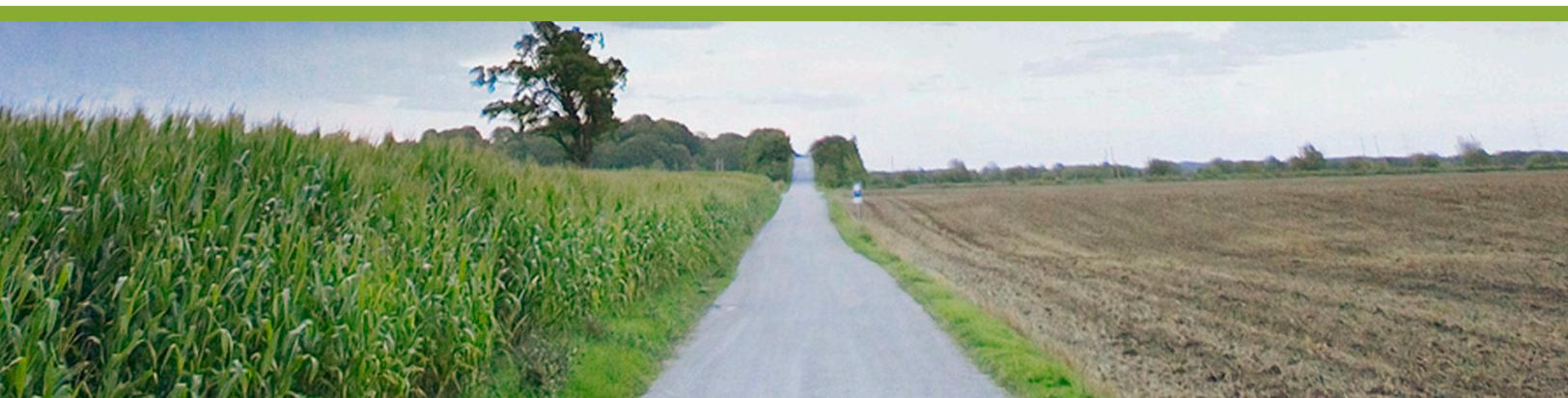
Global events that drove food prices to record highs in 2007 and 2008 served as a reminder that humanity cannot take food production for granted. As a result, agricultural research has been refocused on the goal of producing enough food for the world's population—by ensuring that our crops provide adequate yield. Doing so without exacerbating the harm that industrial agriculture currently imposes on the environment and society, however, will be challenging.

Genetic engineering has been promoted as an important means for dramatically improving the yields of staple food crops, but there is little evidence to support such a claim. In *Failure to Yield*, the Union of Concerned Scientists provides the most comprehensive evaluation to date of more than two decades of U.S. genetic engineering research and commercialization aimed at increasing crop yield. Our analysis shows that despite tremendous effort and expense, genetic engineering has only succeeded in measurably increasing the yield of one major food or livestock feed crop—and this contribution has been small compared with other available methods.

Failure to Yield also considers the substantial theoretical and practical challenges to increasing yield via genetic engineering in coming years, provides an evaluation of more promising approaches that would also minimize environmental harm, and recommends policy changes that would maximize our ability to improve crop productivity in a sustainable manner.

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