FAILURE TO YIELD

Evaluating the Performance of Genetically Engineered Crops

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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

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 dramatically 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

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.