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Genetic Engineering and the Big Challenges for Agriculture - Lessons from the United States

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Scientific Conference 2012
Advancing the Understanding of Biosafety
GMO Risk Assessment, Independent Biosafety Research and Holistic Analysis

28 - 29 September 2012
Hyderabad / India

Introduction

Genetic engineering has been proposed to be a transformative technology, necessary for ensuring that agriculture is sustainable and productive in coming decades. It began in the mid-1980s, almost 30 years ago, and the first commercialized GE crops were grown in the mid-1990s, about 16 years ago. This history provides a record that is now long enough to begin to evaluate the benefits, and to understand the potential of this technology. Genetic engineering (GE) is often evaluated based on direct risks, such as possible harm from consumption or direct harm to beneficial organisms in the environment. But another important criteria for evaluating genetic engineering, or any other practice or technology in agriculture, is how successful it has been in addressing the biggest challenges confronting food and fiber production.

The challenges to agriculture that need to be addressed are widely agreed upon, including producing enough food for a growing population, expected to reach about 9 billion by mid-century. It is important to remember that poverty is the biggest reason why there is hunger in the world. We still produce enough food to feed everyone if equitably distributed. Nonetheless, producing enough food for more people while pressed by climate change is a growing concern. In addition, the greatly increased amount of synthetic nitrogen fertilizer since the 1960s has increased crop productivity, but is causing serious pollution on a global scale, including several hundred hypoxic “dead zones” in coastal waters.

Another challenge is climate change, which may exacerbate drought in some regions, as well as more extreme weather events including flooding and high temperatures. Agriculture already uses about 70 percent of extracted fresh water, with some important sources such as aquifers being depleted more rapidly than they are being recharged. Therefore, reduction of water use and more resilience in the face of drought and temperature extremes are additional important challenges for agriculture in coming decades. To assess the progress and value of GE, we have evaluated the impact of genetic engineering in the U.S. on three important challenges to agriculture: increasing food productivity, increasing nitrogen use efficiency, and increasing drought tolerance. These serve as indicators of how successful genetic engineering has been at addressing major challenges that must be solved if our food production system is to be sustainable and productive enough to serve humanity.

Genetic Engineering and Crop Productivity in the U.S

To evaluate the contribution of GE to crop yield, we evaluated peer-reviewed science research and data from the US Department of Agriculture on the yield of genetically engineered corn (maize), containing Bt genes or herbicide tolerant soybeans (resistant to glyphosate herbicide) (Gurian-Sherman 2009). These are the two crops of greatest acreage in the U.S., with cotton between five and 10 percent of the acreage of these two crops. When considering yield and genetic engineering, it is critically important to separate out the effects of the engineered gene(s) from other factors that influence yield. These other factors include the yield of the crop variety that the genes are inserted into, and crop management practices.

The yield effects of the crop variety are especially difficult to separate from the effects of the transgene, because both are encompassed in the growth of the plant and not readily separated from each other. Farmers, for example, may buy a new engineered crop variety and obtain higher yields than for a previous non-engineered variety. It would be natural to attribute these yield gains to the engineered gene, when typically the crop variety that the gene has been placed into is already improved for yield compared to the older variety. The most accurate and direct way to distinguish the contribution of the transgene from that of the crop variety is in controlled side-by-side field or farm trials that use typical farming practices, and where some fields contain the crop variety with the transgene, and others the same variety without the gene.

We emphasized these types of studies, but also relied on other field data, such as regional data on the periodicity of European corn borer (ECB) infestations in the corn belt, to inform our analysis. We found that the two primary types of Bt in corn, to control ECB and rootworms, contributed about three to four percent to the total productivity of corn in the U.S. Individual farmers may receive greater benefit if they encounter heavy insect infestations, but these occur sporadically. For corn borer, only about once every four to eight years, and for rootworm in most areas, only when corn is planted year after year. When the productivity contribution for all acres is estimated, this results in a three to four percent aggregate productivity increase. This value is important because it is aggregate productivity that is relevant to society from the perspective of whether we produce enough grain to feed ourselves. Higher yield for some individual farmers is, clearly important to those farmers. We also found that available data did not support an increase in yield due to the glyphosate herbicide tolerance gene in corn. Therefore, the total impact on corn productivity is estimated to be about three to four percent over the first 12 years of commercialization, from 1996 through 2008.

By comparison, data from the USDA show that corn productivity increased by about 28 percent over the same period of time. Therefore, of the 28 percent increase in corn productivity between 1996 and 2008, about 24 or 25 percent was due to factors other than GE. This is about 86 percent of the total increase in yield in corn in those years. Factors that typically increase crop productivity fall into two general categories: crop breeding and improve agronomy. Historically, about half of the yield increases in corn have been attributed to breeding. GE contributed about 14 percent of the yield increase between 1996 and 2008

Recent published research has calculated that GE traits in corn have contributed about 7 percent yield increase (five percent from Bt and two percent from herbicide tolerance) (Nolan and Santos 2012). Using these values, GE would have provided about 25 percent of the yield increase in corn, while other methods such as breeding collectively provided about 75 percent. For soybeans, we found that the herbicide tolerance gene provided no clear yield advantage, while based on USDA data, yields went up about 16 percent from 1996 – 2008, due to breeding and agronomy. It is also important to understand that yield is often understood as consisting of two general components: intrinsic yield, also called yield potential, and operational yield. The former is generally understood as the yield that can be obtained under favorable conditions in the absence of factors that reduce yield, such as pest infestation or stresses such as drought. The actual, or operational yield, is that obtained under normal growing conditions that include pest infestations and so on, and varies from year to year.

The yield improvements from GE discussed above are from increased operational yield, i.e., reduction of losses from insects and weeds. These are important globally, and especially in many developing countries. On the other hand, while breeding has increased intrinsic yield of corn and soybeans over the decades, GE has not done so. There are so far no GE crops that increase intrinsic yield. The lesson so far is that conventional breeding and agronomy continue to contribute more than GE to increasing crop productivity in the US, where GE can be compared to other advanced agricultural technologies and methods

Reducing Nitrogen Fertilizer Use and Pollution

Synthetic nitrogen fertilizer has greatly increased crop productivity, but at the expense of great harm to the environment. It is also expensive, and is made from natural gas, a nonrenewable fossil fuel that contributes to climate change. The use of nitrogen fertilizers also results in tremendous amounts of water pollution, including several hundred hypoxic “dead zones” in coastal waters that are important for seafood production. Nitrous oxide that is produced in the soil by microbes, from nitrogen fertilizer, is an important and potent greenhouse gas. For all of these reasons, it is important to reduce the use of nitrogen fertilizers. One way to do so is through the development of crops that use nitrogen more efficiently. Genetic engineering has been touted as one important way to develop nitrogen use efficient (NUE) crops. Our analysis of the scientific literature found that despite field trails for about a decade, no crop engineered for NUE has been successfully commercialized (Gurian-Sherman and Gurwick 2009). There had been, as of 2009, about 125 field trials for NUE crops, as compared to thousands for insect or herbicide resistance, indicating many fewer prospects for NUE. On the other hand, the scientific literature has shown that over the past several decades, NUE has increased for several major crops through breeding and other means by about 30 to 40 percent.

Our analysis of the scientific literature of the genes being considered for improved NUE through GE shows that most are plant genes that are found in crops. In addition, studies over the past two decades have demonstrated that there is considerable genetic variation in crop plants and their wild relatives, including for NUE, that may be tapped into to further improve NUE through conventional breeding. More importantly, non-genetic means of reducing the need for synthetic nitrogen, and the pollution it causes, are available. These include the use of cover crops that can reduce pollution from nitrogen leaching into groundwater by about 40 to 70 percent, and the use of legumes to supply organic nitrogen to crops.

Drought Tolerance and Water Use Efficiency (WUE)

Drought, along with high temperature, is the single biggest cause of losses of food productivity globally. Predictions of more frequent or severe droughts and more frequent high temperature extremes with increasing climate change in coming decades means that these losses could increase at a time when more food is needed. In addition, agriculture is already the greatest user of water, accounting for about 70 percent of extracted fresh water use. This is stressing many water sources and causing competition for other human and wildlife needs. As with other agricultural challenges, genetic engineering has been proposed as an important and necessary means of confronting the challenges of drought and for improving WUE.

We recently analyzed the data on the contributions of genetic engineering to drought tolerance from the science literature and the USDA, as well as from the submission of data by Monsanto Co. to the USDA to support regulatory approval for drought tolerant GE corn, called DroughtGard (Gurian-Sherman 2012). Drought is complex, and can vary in severity and timing depending on its duration, when in the growth cycle of the crop the drought strikes, soil conditions, and other factors. Plants can also respond to drought in many ways, such as by increasing root capacity or length, limiting water loss through reduced transpiration (loss from the plant), reducing the timing of particularly susceptible stages of growth, such as flowering and seed filling in grain plants, and so on. The large number of different crop responses to drought reduces the possibility that a single, or even several, drought tolerance genes will be useful for all droughts or provide dramatic tolerance. This is borne out from limited data supplied by Monsanto to USDA, which show that its drought tolerant corn may provide approximately a six percent reduction in yield loss on land experiencing moderate drought. For example, instead of experiencing a 15 percent yield loss, such corn may experience about a 10 percent loss. In other words, in a typical year, where this type of corn may be grown on about 15 percent of U.S. corn acres, it would provide about a one percent productivity benefit nationwide.

By contrast data from research from Iowa State University shows that conventional methods have increased drought tolerance in corn over the past 30 years by about one percent per year. Other data show that many crops, including several varieties of corn, are benefiting from increased drought tolerance through conventional breeding. These include sorghum, cassava, rice, pearl millet, wheat, and corn. Other studies show that, as with NUE and yield, substantial untapped genetic variation exists in crops and their wild relatives for improving drought tolerance. Drought tolerance may also be improved through sustainable farming practices like organic and low-external-input systems that emphasize cover crops, crop rotation, including trees and other perennials in the cropping system, and use of livestock manures. All of these practices increase soil fertility, which increases the water holding capacity of soil, making this moisture available during droughts.

Water use efficiency is also important, and has often been incorrectly considered to be synonymous with drought tolerance. Rather, scientists who study WUE have pointed out that most drought tolerant crops have ways to prevent the plant from having reduced yields during drought, but this typically requires as much water per unit of food produced as is required by non-drought tolerant crops. WUE and drought tolerance are therefore not typically the same thing, and most drought tolerance traits do not improve WUE. Based on data provided to USDA by Monsanto, this is the case for DroughtGard. Under normal water availability, DroughGard does not reduce corn water requirements. If water supply is reduced, DroughGard may use somewhat less water to produce a kilogram of corn than for normal corn, but at the expense of reduced yield, which is undesirable. As a whole, the GE industry has invested very little in producing WUE crops. There have been only nine field tests for GE WUE since 1990, compared with about 8,000 for insect resistance and herbicide tolerance.

What about the Future: The Prospects for GE in Coming Years

Several lessons can be learned from our analyses of GE crops. First, the technology has made only very minor progress toward addressing the big challenges for agriculture now and in coming years. Some have argued that this is because the technology is relatively new, and that we should have confidence that it will improve in the future. But the technology is now about 30 years old—not such a new comer—and there are biological reasons, which are discussed below, for harboring some skepticism about the prospects of GE in the future.

Second, crop breeding and better, agrocologically-based, farming practices are much more effective than GE at confronting agriculture's challenges. In addition, those technologies are far cheaper than GE. For example, the industry's own analysis found that a typical GE trait costs about 140 million dollars to develop, while a similar trait costs about one million dollars to develop through breeding. Studies over the past two decades have demonstrated, contrary to previous belief, that crops have a large amount of genetic diversity that can be tapped to help address agriculture's challenges. The first few commercially successful engineered traits, Bt insect resistance and herbicide tolerance, are genetically and physiologically relatively simple. Bt codes directly for a protein toxin that directly kills some insects when eaten. A single gene that is not inhibited by glyphosate herbicide is responsible for glyphosate herbicide resistance.

By contrast, many of the traits that are important for making agricultural more sustainable, better for the environment, and more resilient and productive, are complex genetically and physiologically. For example, many genes contribute to yield or drought tolerance. This generally has at least two important implications for genetic engineering.

First, this means that any given engineered gene is likely to have only a modest effect on traits like drought tolerance or intrinsic yield improvement, because it can affect only some of the responses that plants can use to improve the trait. There are some types of single genes, such as so-called transcription factors, that can affect the function of numerous other genes. But even these are not likely to affect most of the routes that can improve these complex traits.

Second, many of the effects of genes like transcription factors may reduce the function of other, agronomically useful traits at the same time that they improve a target trait such as drought tolerance. This is because some of the genes that are affected by the engineered gene are not those that are the intended target of the engineering. This is called pleiotropy by geneticists, and its ramifications are not readily predictable. Although data are scare, there are instances where negative pleiotropy or negative impact on gene function, some of which are documented in our reports, has been observed for some of these engineered genes. In many cases, we will not know whether such negative pleiotropy exists until after extensive field trials, or more likely, commercial planting for several years.

There are no easy solutions for these two challenges going forward. Probably GE will, as is the case for DroughtGard, continue to make modest progress on these traits for the foreseeable future. But as we have seen, breeding, which can manipulate several genes at a time, is likely to do better. And nether type of genetic improvement can replace improved, sustainable farming practices.

Conclusions and Further Thoughts

Genetic engineering has made some minor contributions toward addressing major challenges in agriculture. These are often discussed uncritically by the media and many scientists in ways that magnify and distort the contributions of GE. This occurs because the small magnitude of the contributions are often glossed over, and especially because they are almost never discussed by proponents of GE in the context of other approaches to agriculture that are proven, like breeding, or show much more promise, and much better results, at lower cost. At other times, numbers are presented in a way that also magnifies their importance. For example, it has been said that about 13 million small farmers use GE. Without context, this sounds impressive. But when framed by an understanding that there are up to two billion people engaged in farming or related activities worldwide, the percentage of farmers using GE is shown to be very small. This problem is exemplified by comparisons of GE to conventional industrial monoculture agriculture, which while productive is not sustainable, and already causes huge environmental and public health problems. Studies that show minor improvements compared to these types of agriculture myopically magnify the value GE. By contrast, as our work has shown, when breeding and agroecology are contrasted with GE, the latter shrinks in importance.

In addition, GE has reinforced the industrial model of agriculture. Higher input costs from more expensive seeds may result in a relatively larger percentage of profits going to large seed companies. This is a pattern repeated by other farming input industries and technologies (as well as by large food processors and aggregators). This forces farms that grow commodity grain crops in the U.S. to continue to grow in size to make more money on higher volume. And current GE crops, by reducing labor inputs, facilitate this trend. But the increasing simplification of agriculture systems that result from this ongoing process are the opposite of farms based on sound biology and ecology, which is facilitated by biological complexity, such as longer crop rotations, the use of cover crops and trees, which reduces pest problems and recycles crops nutrients. These latter functions improve sustainability and resilience and reduce cost to farmers, but are generally not favored by big companies because they rely more on knowledge than products that those companies sell.

The problems that result from this decreased biological complexity, in addition to the environmental impacts of nitrogen that have already been discussed, are the rise of herbicide resistant weeds in the U.S. due to the excessive use of herbicides on GE crops, and now the advent of resistant insects. The answer from GE seed companies is more herbicide resistant crops, using older herbicides, which will greatly increase herbicide use. This pesticide treadmill is ultimately not sustainable (Mortensen et al. 2012). Resistance to herbicides and insecticides has always occurred in industrial agriculture. But that GE also has this serious problem is a compelling argument against it. And in addition, the scale of resistance of weeds due to use of glyphosate on GE corps greatly exceeds what has come before, and this is directly connected to how these herbicides are used on GE crops.

The answer to these problems is a large shift in the dedication of public resources to those types of agriculture that we know can improve sustainability, resilience, and productivity, and support farmers in their livelihood. These include research, policy incentives, and information on agroecology and breeding, especially participatory breeding. Genetic engineering can make small contributions, but at great cost. As such it is largely a distraction from better approaches to agriculture. But since it is one favored by the economically and politically powerful companies that sell GE seed, only an informed process supported by popular demand is likely to reverse the overemphasis on GE technology at the expense of vitally important alternatives.

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