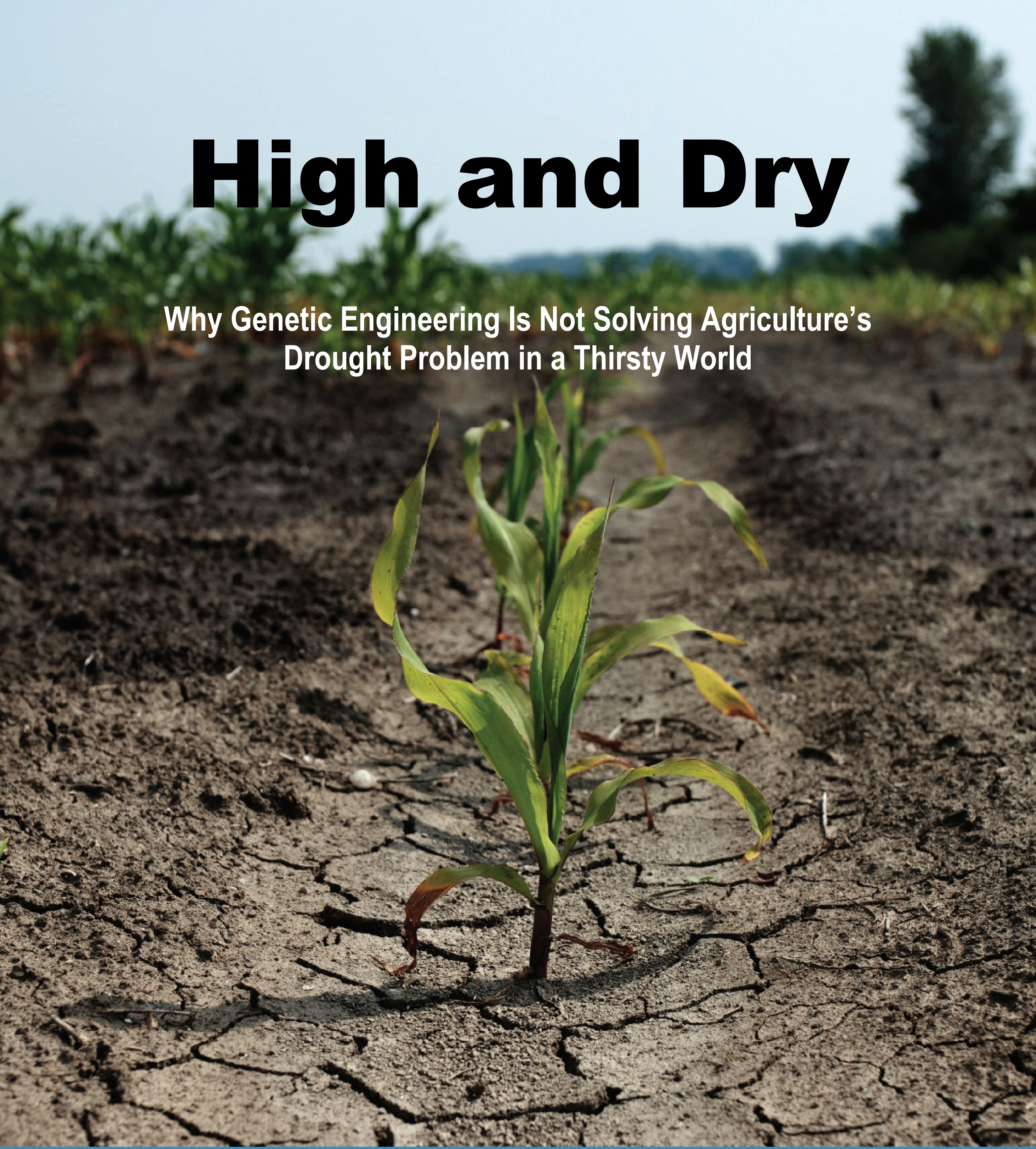


High and Dry

Why Genetic Engineering Is Not Solving Agriculture's Drought Problem in a Thirsty World

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

High and Dry

Why Genetic Engineering Is Not Solving Agriculture's Drought Problem in a Thirsty World

Doug Gurian-Sherman

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

June 2012

Doug Gurian-Sherman is a senior scientist in the Food and Environment Program of the Union of Concerned Scientists.

The Union of Concerned Scientists (UCS) is the leading science-based nonprofit working for a healthy environment and a safer world. UCS combines independent scientific research and citizen action to develop innovative, practical solutions and secure responsible changes in government policy, corporate practices, and consumer choices.

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.

More information is available on the UCS website at *www.ucsusa.org/food_and_agriculture*.

This report is available on the UCS website (*www.ucsusa.org/publications*) or may be obtained from:

UCS Publications
2 Brattle Square
Cambridge, MA 02238-9105

Or, email *pubs@ucsusa.org* or call (617) 547-5552.

Cover photo: © iStockphoto.com/Drbouz

Contents

Figures

Acknowledgments

This report is dedicated to my partner and spouse, Stacey, and my daughter, Shoshana. Without their unwavering support and encouragement, this report would not have been possible.

This report was made possible in part through the generous support of the C.S. Fund, the Clif Bar Family Foundation, the Cornerstone Campaign, the David B. Gold Foundation, the Deer Creek Foundation, the Tomchin Family Charitable Foundation, and UCS members.

For their thoughtful reviews of the report, the author would like to thank Major Goodman, North Carolina State University; Frank Kutka, North Dakota State University, and Seth Murray, Texas A&M University. The time entailed in reviewing a report of this length is considerable, and their comments and suggestions greatly improved it.

At UCS, the author thanks Jane Rissler, who provided two of the figures, scientific literature searches, and most of the USDA field trial data. The author also thanks Margaret Mellon and Kathy Rest for their reviews of the report, Erika Spanger-Siegfried and Nadia Madden for their comments on the executive summary, and Heather Sisan for general assistance. Karen Perry-Stillerman's editing of the executive summary, and her managerial efforts to keep the report on track, were invaluable. The advice, encouragement, and helpful edits of these colleagues influenced and improved the report's final form.

We would also like to thank Sandra Hackman for careful and precise copyediting, and Rob Catalano for his design and layout of the executive summary.

The opinions and information in this report are the sole responsibility of the author, and do not necessarily reflect the opinions of the foundations that supported it or the individuals who reviewed and commented on it.

Executive Summary

Droughts—periods of abnormally dry weather—can be devastating to farmers and food production. The historic Texas drought of 2011 caused a record $5.2 billion in agricultural losses, for example, making it the most costly drought on record. Similar crippling droughts have recently occurred around the world, and climate scientists expect the frequency and severity of droughts to increase, sometimes unpredictably, in some regions as the global climate heats up. Although extreme droughts receive the most attention, mild to moderate droughts actually affect more acreage, and also cause substantial crop losses.

Agriculture accounts for the lion's share of all water extracted from rivers and wells—about 70 percent—setting up conflicts between food production and other uses. And beyond competition for water among various human needs are the requirements of aquatic organisms, such as game fish prized by sportspeople, who bring dollars to local economies. Finding ways to protect food production and farmers' livelihoods from devastation by drought—and also to reduce agriculture's need for water—is therefore vital.

The Union of Concerned Scientists (UCS) analyzed the prospects for improving crops in ways that can reduce water use overall, and losses during dry periods. We focused on crop genetic engineering—the lab-based manipulation of genes from any source to alter plants. Practitioners and proponents have touted the potential of genetic engineering to address drought. Biotech companies, including Monsanto, have promised to deliver new crop varieties engineered with novel genes that enable them to thrive under drought conditions.

The biotech industry has also suggested that genetic engineering can reduce demand for water from crops even under normal conditions—resulting in "more crop per drop." However, we found little evidence of progress in making crops more water efficient. We also found that the overall prospects for genetic engineering to significantly address agriculture's drought and water-use challenges are modest at best.

Genetic Engineering Offers Modest Results…at High Cost

The biotech industry has so far received regulatory approval—in December 2011—for only one crop engineered for drought tolerance. Available data show that Monsanto's so-called DroughtGard corn produces only modest results. And according to data supplied by Monsanto and analysis by the U.S. Department of Agriculture (USDA), the variety does so under only moderate drought conditions. In fact, despite what the industry may have hoped, this product—and this technology—are not a panacea for drought.

Drought presents a particular challenge for genetic engineering because it can take many forms. Droughts vary in their severity and their timing in relation to crop growth. Related factors such as soil quality affect the ability of crops to withstand drought. These complications make it unlikely that any single approach or gene used to make a genetically engineered (GE) crop will be useful in all—or even most—types of drought. What's more, many genes control drought tolerance in plants—a particular challenge for genetic engineering, which so far can manipulate only a few genes at a time.

Evidence is also scant that the technology will help crops and farmers use water more efficiently in the foreseeable future. Very few experimental GE crops have been designed to use water more efficiently, and none are approaching commercialization.

In an era of reduced government spending, the cost-effectiveness of different technologies for improving agriculture—often supported by public research funding—is important. We found that although genetic engineering is beginning to have some success in enhancing the drought tolerance of crops such as corn, other technologies, such as classical and newer forms of breeding, continue to be more effective, at lower cost.

Improved farming practices are also likely to be more effective in enhancing the ability of crops to withstand drought. Crop management practices complement genetic approaches such as breeding and genetic engineering, and should receive more public support in the form of government research and incentives. An excessive focus on genetic engineering at the expense of other approaches risks leaving farmers and the public high and dry when it comes to ensuring that the United States and other nations can produce enough food, and have enough clean freshwater, to meet everyone's needs.

Major Findings

To produce this report, we analyzed scientific studies on GE drought tolerance and crop breeding, and the USDA's database on field trials of drought-tolerant GE crops. We also reviewed Monsanto's 2009 petition for approval of DroughtGard, and the USDA's environmental assessment based on that petition.

These sources showed that scientists engineered several types of genes, mostly from plants, for drought tolerance in the late 1990s and early 2000s. By the middle of that decade, researchers were using drought-specific gene switches, called promoters, to control when and how strongly the engineered genes are turned on. Other findings:

- The annual number of USDA-regulated field trials of crops engineered for drought tolerance remained below 20 from 1998 to 2003. That number spiked to 82 in 2005, and remained between 82 and 113 for seven years, including 90 trials as of late 2011.

- Developing a new GE trait typically takes about 10 to 15 years, including several years prior to field trials. Given the surge in field trials beginning in 2005, several drought-tolerance genes should be nearing approval and commercialization, if these crops have proved effective and reliable in field trials. However, as noted, the USDA has approved only one GE drought-tolerance gene and crop variety for commercial use, and no others have been submitted for approval.

- Monsanto's DroughtGard corn contains a gene called *cspB*. According to the USDA's environmental assessment and available data, *cspB* corn is not expected to be of practical value in severe or extreme drought.

- Monsanto's gene will confer only modest protection against moderate drought—about 6 percent more than non-engineered varieties used in Monsanto's test plots five or six years ago. This outcome, based on only two years of field trials with widely varying results, may not accurately predict the level of drought tolerance once the product is grown more widely.

- By comparison, classical breeding techniques and improved farming practices have increased drought tolerance in U.S. corn by an estimated 1 percent per year over the past several decades, according to one recent study (due to the challenges of measuring drought tolerance, this value should be considered a rough estimate).

- That means traditional methods of improving drought tolerance may have been two to three times as effective as genetic engineering, considering the 10 to 15 years typically required to produce a genetically engineered crop. If traditional approaches have improved corn's drought tolerance by just 0.3 percent to 0.4 percent per year, they have provided as much extra drought protection as Monsanto's GE corn over the period required to develop it.

- Farmers are expected to plant *cspB* on only about 15 percent of corn acres in the United States. If this corn reduces the yield normally lost during drought by 6 percent on 15 percent of corn acres, it would increase corn productivity nationwide by about 1 percent. That improvement is about the same as the increase in drought tolerance in a single typical year achieved through conventional means, as determined by the study noted above, and only about half of the nearly 2 percent overall annual yield increase of corn in the United States.

- Although data are limited, Monsanto's *cspB* corn does not appear to be superior to several recent classically bred varieties of drought-tolerant corn.

- Although Monsanto has said it has a goal of getting "more crop per drop," its *cspB* corn does not appear to have improved water use efficiency (WUE): the ability of a crop to use less water. The company has not supplied any data measuring water use by *cspB* corn, or otherwise suggested that it has improved WUE. Drought tolerant crops typically do not require less water to produce a given amount of food or fiber.

- In all, the USDA has approved only nine field trials designed to evaluate the WUE of several different engineered crops since 1990. This strongly suggests that improved WUE—independent of drought tolerance—is not a serious goal of the biotech industry.

- Several food and feed crops, such as sorghum or pearl millet, are naturally more drought tolerant than corn. These crops are often less productive than crops more familiar in the United States—probably partly because they have received more limited attention from crop breeders. Many have untapped potential for improved yields and other desirable traits, suggesting opportunities to use them more widely in dry regions around the world.

The Challenges of Enabling Crops to Withstand Drought

In contrast to other GE crops now on the market, such as insect-resistant and herbicide-tolerant crops, drought tolerance requires the interaction of many genes. And genetic engineering can manipulate only a few genes at a time.

Some individual genes can affect genetically complex traits such as drought tolerance. However, even if genetic engineering can improve the drought tolerance of crops somewhat, it may not be enough to substantially reduce crop losses in the real world, where drought can vary in severity and duration. Any given engineered gene is likely to address only some types of drought, and then only to a limited extent.

And genetic approaches—whether genetic engineering or traditional breeding—are unlikely to substantially mitigate losses from severe or extreme droughts in the foreseeable future. That is because traits that provide substantial tolerance under extreme drought greatly reduce plant growth rates, limiting crop yields.

Yet severe to extreme drought is a significant piece of the drought problem farmers are facing. According to the National Climatic Data Center, severe to extreme drought affected about 23 percent of the contiguous United States in October 2011.

Furthermore, genes involved in drought tolerance often interact in complex and unexpected ways to alter more than one trait. Geneticists call this phenomenon pleiotropy. It can mean that engineered drought-tolerance genes produce additional, undesirable effects on crop growth.

Scientists can reduce harmful pleiotropy by enabling engineered genes to turn on only during drought. However, because droughts are often prolonged, this approach is unlikely to eliminate these harmful effects. Limited field trials and greenhouse tests of GE drought-tolerant crops could miss such effects, which could arise after commercialization.

The Uncertain Market for GE Drought-Tolerant Crops

The number of GE drought-tolerant crop varieties that appear on the market over the next five years should indicate whether the technology, at this stage of its development, can substantially improve this trait. The stalled number of GE field trials for drought-tolerant varieties since 2005 suggests that the pace of discovery of drought-tolerant genes may have slowed, although other explanations are possible.

Several obstacles may limit the commercial success of Monsanto's *cspB* corn. First, DroughtGard is likely to face competition from varieties of drought-tolerant corn produced through less expensive breeding methods. Markets for *cspB* corn and other drought-tolerant varieties will also depend on their other traits, such as overall yield and pest resistance. On the other hand, cross-licensing of the *cspB* trait by other companies, as has occurred with previous engineered genes, could expand its market by reducing competition from other varieties.

Another challenge for *cspB* corn is that farmers buy their seeds well before they plant. Because drought is not reliably predictable, many farmers may not want to pay the higher price of DroughtGard seeds just in case drought occurs. This may restrict planting of *cspB* corn mainly to areas where moderate drought is frequent, such as the western regions of the Corn Belt, which account for about 15 percent of U.S. corn acres.

Herbicide-tolerant or insect-resistant crops can save farmers time and money by reducing chemical pesticide applications, despite higher initial seed costs. However, these factors are unlikely to occur with GE drought-tolerant corn, and are therefore unlikely to drive its sales.

For all these reasons, the markets for DroughtGard corn, and any other engineered drought tolerant crops, are uncertain.

Recommendations

Given the status of R&D on GE drought tolerance and challenging questions about its prospects, UCS recommends that:

- Congress and the USDA should substantially increase support for public crop-breeding programs to improve drought tolerance. Because large seed companies focus mainly on engineered crops, this would give farmers better access to non-GE drought-tolerant varieties.

- Congress and the USDA should use conservation programs funded under the federal Farm Bill to expand the use of available methods for improving drought tolerance and WUE. These include the use of water-conserving irrigation equipment, which may require considerable investment on the part of farmers, and farming methods that increase soil organic matter, which farmers must consistently use over several years to see substantial benefits. The Farm Bill can offer incentives or subsidies to help farmers at risk of drought adopt such practices.

- The USDA and public universities should increase research devoted to finding better ways to store and conserve soil, groundwater, and surface water, and better farming methods to withstand drought.

- Public and private research institutions should devote more funding and effort to crops that are important in drought-prone regions in the Southern Hemisphere. These crops, which include sorghum, pearl millet, cassava, and cowpeas, are inherently more drought-tolerant than crops familiar in the Northern Hemisphere.

- Researchers at the USDA and public universities should carefully monitor the efficacy and possible undesirable effects of *cspB* corn. Such monitoring is important because this variety is the first GE commercial drought-tolerant crop, and the resulting information would enhance our understanding of GE drought tolerance. Similar monitoring should occur for any other GE drought-tolerant crops.

- The USDA and public universities should expand their research on using plant breeding to improve water use efficiency—a vital concern that has not attracted major efforts from the biotechnology industry. The public sector should also invest in improving water-saving irrigation methods and the water-holding capacity of soil, reducing water loss from soil, and developing better water storage facilities.

Chapter 1

Introduction

Humanity faces a steep challenge this century: increasing food production without causing tremendous harm to the environment. Advocates of genetic engineering have promoted it as an important way to meet this challenge.

In two previous reports, the Union of Concerned Scientists (UCS) examined claims that genetic engineering could increase the yield of crops, and improve the efficiency by which they use nitrogen (Gurian-Sherman 2009; Gurian-Sherman and Gurwick 2009). We concluded that genetically engineered (GE) traits increase the overall yield of corn modestly, and do not increase the yield of soybeans—the two major U.S. crops. We also found no GE products on the market, and relatively few in the pipeline, that boost the efficiency by which crops use nitrogen.

Classical breeding and improved farming practices, in contrast, have delivered improvements for decades in both crop yield and the efficiency by which crops use nitrogen. And researchers are continuing to harness these techniques to bolster these traits. In fact, scientists can use new molecular and statistical tools to identify native genetic diversity for these traits—an approach that may cut the time and cost of improving crops through classical breeding.

This report analyzes the existing record and future potential of crops genetically engineered for drought tolerance, compared with advances made possible by conventional breeding. We base our analysis of GE crops on public records of field trials approved by the U.S. Department of Agriculture (USDA), applications to the agency for regulatory approval to sell such crops, and scientific studies.

Roadmap to the Report

Chapter 2 explores the complexity and impact of drought, and introduces the three major approaches to combating it: GE crop varieties, conventional crop breeding, and agroecosystem management. The chapter also examines the challenges of evaluating the drought tolerance of crops, and the relationship between drought tolerance and the efficiency with which plants use water to produce a unit of food, feed, or fiber.

Chapter 3 focuses on the status of drought-tolerant crops, and evaluates the only GE variety that has received regulatory approval and is nearing commercialization: corn containing the bacterial gene *cspB*, developed by Monsanto. We base our analysis on information in Monsanto's petition to the USDA for approval to sell seeds of this corn, an environmental assessment produced by the agency, and scientific studies.

Chapter 4 explores the future prospects of GE drought-tolerant crops, including the challenges of modifying complex traits in crops.

Chapter 5 summarizes our findings and proposes important steps policy makers can take to enable crops to withstand drought.

Chapter 2

The Complexity of Drought and Efforts to Address It

Drought is one of the most serious causes of lost crop productivity globally, although exact figures for these losses depend on the definition of drought. In the United States, insurance payments to farmers to cover crop losses stemming from drought totaled nearly $3 billion in 2002 (Wilhite, Svoboda, and Hayes 2007).

In years when serious droughts occur in major food-producing regions, crop losses can affect the global food supply and food prices. This occurred in 2008, when Australia, a major global wheat producer, lost substantial production because of severe drought (Headey and Fan 2008).

Scientists project that global warming will create or worsen water scarcity in some regions (Rijsberman 2006)—often those that already suffer from food challenges. Meanwhile expanding populations and growing consumption of animal products, driven by rising incomes, require more production of pasture crops and feed grains, further stressing water supplies used for agriculture.

In this report, we define drought as any reduction in the amount of water available for crop production—independent of irrigation—that reduces crop yield below what farmers could produce with adequate water. Although drought seems like a straightforward phenomenon, its effects are complex (Wilhite, Svoboda, and Hayes 2007; Richards 2006; Araus et al. 2002). For example, how long a drought lasts, its timing in relation to the stages of crop growth, the water-holding capacity of soil, daytime and nighttime temperatures, and the types of crops farmers grow all affect the impact of drought on food production.

Severe or extreme droughts—those that last for months or years—often attract the most attention. However, mild and moderate droughts are more common, and exert a substantial impact on crop production, especially when they occur during critical mid-summer periods when grain crops flower and produce seeds.

Yet severe to extreme drought is a significant piece of the drought problem farmers are facing. According to the National Climatic Data Center, severe to extreme drought affected about 23 percent of the contiguous United States in October 2011.

Neither conventional breeding nor genetic engineering can harness the suite of traits used by desert plants to prevent a drop in crop yield during extreme drought, because desert plants sacrifice rapid growth during dry seasons to survive. Even if scientists could breed or engineer crop plants to have those traits, their low productivity would be unacceptable.

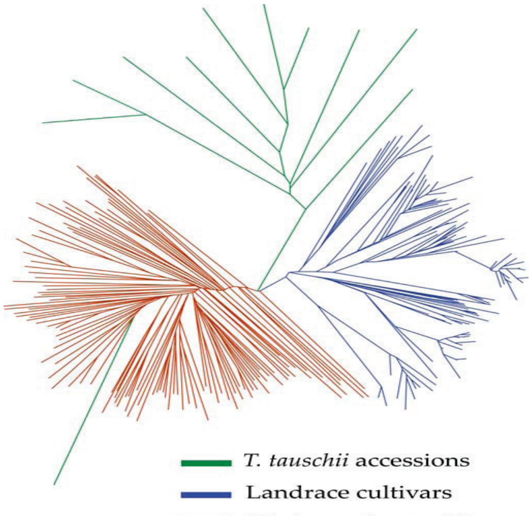
These complexities have important implications for how to mitigate the harm droughts cause, and for the potential of both genetic engineering and conventional breeding to reduce their impact.

Major Approaches to Reducing the Impact of Drought

Scientists and farmers can use several approaches to help crops withstand drought. We can broadly separate these into genetic methods, which help crops tolerate drought, and agronomic or agroecological approaches, which alter farming methods or the environment in which crops grow to reduce their susceptibility to drought.

Scientists rely on two overall approaches to harnessing genetics to make crops more drought tolerant: conventional crop breeding, including newer genomics-based approaches; and genetic engineering. Although these methods overlap, breeding focuses on genes from the same crop species, or from closely related species that can successfully mate with the crop. Even newer genomic methods such as marker-assisted selection, which use molecular data to assist the breeding process, rely on mating to recombine genes from closely related plants. These methods use unique patterns in the DNA sequences associated with traits such as drought tolerance as a kind of molecular fingerprint to follow the traits through the breeding process. This can allow breeders to forego some of the time-consuming processes used to detect the traits, which can be hard to identify, in the field.

Figure 1. Genetic Diversity among Plants That Can Be Used in Wheat Breeding



Source: Reif et al. 2005.

The genetic relationship between modern wheat and related plants is roughly proportional to the distance between them on this Fitch-Margoliash phylogenetic (relatedness) tree. Landraces are varieties cultivated over long periods of time by farmers in particular locations, and accessions are different examples of the sexually compatible wild relative, Triticum tauschii.

Genetic engineering, in contrast, has two major features: in vitro manipulation of genes from crops or unrelated organisms such as bacteria, and their insertion into crops. This report focuses on genetic engineering in the context of opportunities afforded by conventional breeding.

Genetic Approaches to Improving Drought Tolerance

Conventional breeding harnesses naturally occurring genetic variability within a crop species or its wild relatives to supply traits such as drought tolerance. Several studies have shown that crops such as rice, maize, and wheat—and their sexually compatible wild relatives—harbor substantial untapped genetic potential for breeding, including traits for withstanding drought (Figure 1) (Collins, Tardieu, and Tuberosa 2008; Garris et al. 2005; Reif et al. 2005; Liu et al. 2003; Tanksley and Nelson 1996).

Other studies have identified specific genetic markers and physiological traits associated with drought tolerance in crops or their wild relatives (Araus et al. 2008, Collins, Tardieu, and Tuberosa 2008; Trethowan and Mujeeb-Kazi 2008; Tuberosa and Salvi 2006; Edmeades et al. 1999). Different varieties of barley show up to a 19-fold difference in the expression of genes associated with drought tolerance (von Korff et al. 2009).

Conventional breeding has steadily improved the yield of corn, wheat, and rice under drought conditions. For example, open-pollinated, drought-tolerant varieties of corn released in Malawi in 2009 reportedly had much higher productivity than varieties without improved drought tolerance (CIMMYT no date), and earlier work with tropical maize reportedly produced similar results (Edmeades et al. 1999).

Pioneer Hybrid International has developed conventionally bred drought-tolerant corn varieties with a reported 5 percent yield advantage under some drought conditions (Bennett 2011). And Syngenta claims that its new conventionally bred drought-tolerant corn boosts yields by 15 percent under certain types of drought (Tollefson 2011).

Conventional approaches to breeding sunflower, soybeans, and sorghum for drought tolerance have also had some success (Richards 2006). Several of these efforts have harnessed traits not directly related to crop water use. For example, improving nitrogen fixation under drought conditions can improve crop yield.

Although experience strongly suggests that conventional breeding can make important crops considerably more drought tolerant, the use of newer breeding approaches is challenging. This is because traits associated with drought tolerance may work well in one variety of a crop, or in certain environments or drought conditions, but not in other varieties or environments. Geneticists and crop breeders call this property "low heritability."

In contrast to conventional breeding, how successful genetic engineering will be in bolstering the ability of crops to withstand drought is unclear. While some engineered genes seem to help crops survive and sustain yields under harsh water stress, few data are available on whether those genes will provide such advantages under milder stress, which is more common (Collins, Tardieu, and Tuberosa 2008). And much of the data have been collected in greenhouses, which cannot adequately replicate drought as it occurs in the field.

Unfortunately, no comparisons between genetic variability in traits associated with drought tolerance in important crops and sexually compatible wild relatives, on the one hand, and genes available through genetic engineering, on the other, are yet available. Thus suggestions that one approach is genetically superior to the other are premature.

The Untapped Potential for Breeding Better Orphan Crops

Some crops are inherently more drought tolerant than others. For example, some "orphan" crops—so named because they have received much less attention from commercial breeders and officials in developed countries—are considerably more drought tolerant than more popular crops such as corn, soy, and rice (National Research Council 2006; National Research Council 1996; Singh and Singh 1995).[1]

Many orphan crops—including sorghum, already the fifth most widely grown crop globally (FAO 1996), pearl millet, cassava, cowpeas, and others—have numerous desirable properties (National Research Council 2008). Like corn, for example, sorghum and millets conduct C4 photosynthesis, which

---

[1] Claims for the drought tolerance of these crops are based largely on their relative ability to grow and produce under hot and dry conditions. However, few studies have directly compared their drought tolerance with that of crops grown in temperate regions, such as corn.

can be more productive in hot climates than C3 photosynthesis, which occurs in crops such as wheat.[2] Orphan crops also provide multiple products desired by people in developing countries that grow them, and can serve many of the functions that more common crops do, such as supplying food for people and livestock.

However, orphan crops usually have much lower yields than more familiar crops, as the latter have been subject to decades of intensive research. That suggests that the large gains in yield that are the rule when breeding conventional crops are likely to occur with orphan crops as well. They are also likely to have considerable untapped potential for improvements in food quality and nutritional content as well as yield. And given knowledge from decades of breeding other crops, progress in achieving these goals may be relatively rapid if nations and companies devote adequate resources to them.

Scientists should therefore devote much more effort to confirming whether orphan crops have higher drought tolerance than familiar temperate-zone crops, and whether improving them may be easier in some cases than improving drought tolerance of crops such as corn and rice. Conventional breeders, including those using methods based on genomics, have already made considerable progress in improving the drought tolerance of several of these crops (IITA 2008; Harris et al. 2007). The availability of more drought-tolerant versions would increase options for farmers, and make production more resilient if farmers added them to crop rotations.

Agronomic and Agroecological Approaches to Combating Drought

Limits on the ability of breeding and genetic engineering to mitigate the effects of drought mean that researchers must also pursue other methods for reducing crop losses. These methods include ecologically based farming practices, such as improving the water-holding capacity of soil by using cover crops that increase the organic content of soil (Brady and Weil 2008; Lotter, Seidel, and Liebhardt 2003; Wander et al. 1994). Using crop or cover crop residues on the soil surface, and growing crops that develop broad canopies to shade the soil, also reduce soil temperature and water evaporation.

Other such techniques include improving the infiltration of water through the soil surface through no-till practices and using supplemental irrigation (Franzluebbers 2002). This category also includes using chemicals that reduce the susceptibility of crops to drought, and mulches that help soil retain moisture.

Practices that can increase the organic content of soil, such as organic farming, may substantially improve yields during drought compared with conventional farming (Lotter, Seidel, and Liebhardt 2003). However, some of these techniques may not be practical in all situations: increasing organic matter appreciably may be challenging in some soils, for example. Still, the potential for ecologically based farming, other agronomic methods, and water conservation to improve drought tolerance suggest that scientists should devote considerable efforts to improving these techniques.

Considering the interactions between agronomy and genetics is also critical to improving drought tolerance. For example, crops or varieties with shallow root systems may not reach deep soils that contain high levels of organic matter—and hence more soil moisture—during droughts. Integrated approaches may provide benefits that each approach alone does not provide.

---

[2] C4 and C3 photosynthesis are named for their primary products. The former produces a four-carbon chain, and the latter a three-carbon chain.

The Challenges of Measuring Drought and Comparing Drought Tolerance

The complexity of drought—its timing, duration, and intensity—is reflected in the variety of measures used to define it (Wilhite, Svoboda, and Hayes 2007; Steinemann 2003; Araus et al. 2002; Heim 2002). Scientists may measure crop growth, soil moisture, precipitation over time (which may or may not incorporate temperature), or combinations of these measures. The definition of different levels of drought may also vary.

Different ways to measure drought—and the lack of a standard measure—lead to challenges in comparing drought tolerance among different crops or varieties. Indeed, claims that a certain crop is drought tolerant sometimes lack actual measurements comparing it to other crops or varieties.

Most simply, drought tolerance is the ability of crops to survive or withstand drought. As noted, however, a more relevant definition for agriculture is the ability of some varieties or species of crops to maintain productivity during drought.

For genetically engineered crops, drought tolerance is the ability of an engineered gene to enable a crop to maintain productivity under drought conditions. For breeding, drought tolerance is the presence of genes or gene variants, called alleles, within some crop varieties, or sexually compatible wild relatives, that confer greater drought tolerance. Breeding allows scientists to bring these genes together with other desirable crop traits, such as high nutritional value, yield, and lodging (uprooting) resistance, and shorter time to maturity.

Drought often reduces crop yield by interfering with different stages of growth—known as phenology (Blum 1996). For example, drought that occurs well before a grain crop flowers can affect yield by reducing the growth of photosynthetic or storage tissues such as stems, which supply nutrients to help the grain develop. Drought that occurs during flowering may curb the viability of pollen, the receptivity of its stigma, and seed set.

Drought-tolerance genes may be effective at different stages of growth, or during all stages. These genes may also be expressed only during drought (that is, they are induced), or expressed at all times (that is, they are constitutive).

These variations make comparing drought-tolerant crops difficult. For example, if drought occurs or is more intense during one stage of crop growth, a crop variety with tolerance for that stage may appear to be more drought tolerant than a crop variety with tolerance for a different stage. However, a year in which drought occurs at a different growth stage may favor the other variety.

If drought is more prevalent or important during certain growth stages of some crops or in some regions, some drought-tolerance traits may be more relevant than others. For example, Mediterranean climates experience “terminal” drought: rains are infrequent during summer months. Other climates may receive some precipitation during the growing season. Because the requirements for drought tolerance vary with the type of drought, most traits conferring it will not be useful in all situations.

Because drought can vary widely among regions, and drought tolerance can vary widely among crops, accurately assessing the drought tolerance of different crops and varieties requires extensive field trials over a number of growing seasons in varied environments. Greenhouse studies of GE drought-tolerant crops are of minimal value in measuring drought tolerance in a farming environment: greenhouses simply cannot replicate the complex interactions that occur in the field.

Field trials of GE drought-tolerant crops have so far been limited, although some have found positive results (Yang et al. 2010). Most results reported for these crops come from greenhouse studies, and must be considered cautiously.

Drought Tolerance and Water-Use Efficiency

Water used in agriculture, such as for irrigation, accounts for about 70 percent of human water use (Calzadilla, Rehdanz, and Tol 2010**).** If less water is needed to produce food, more may be available for other human needs—especially important given rising populations and demand for water. Reducing the amount of water used for agriculture could also allow higher stream flows, which could replenish aquifers and preserve aquatic biodiversity.

In several parts of the world, farmers have relied on groundwater in ancient aquifers with very slow recharge rates to irrigate their crops. In several important food-producing regions, such as the Great Plains of the United States and parts of China, farmers are harvesting groundwater for agriculture more quickly than precipitation is replacing it (Sophocleous 2010; Jiang 2009), which could threaten production and raise costs. Crop production may even disappear in some regions when water becomes unavailable or too expensive, as it has in parts of once-productive North Texas.

Climate change may also reduce the availability of freshwater in regions where precipitation declines, or where alpine snowpack or glacial sources of rivers and groundwater dry up because of reduced snowfall or higher temperatures.

For all these reasons, water-use efficiency (WUE)—the amount of crop produced per unit of added or available water—is vitally important. Some drought-tolerant crops may use water more efficiently. However, drought-tolerant plants typically do not have higher WUE, and some have lower WUE (Long and Ort 2010; Blum 2009).

Enabling crops to tolerate the effects of drought, such as dehydration, may often be easier than increasing their WUE (Long and Ort 2010), although this may vary among crops. The fact that governments often subsidize water prices or otherwise keep them low has also reduced the incentive to develop crops with improved WUE. Both drought tolerance and WUE are important, and scientists, farmers, and policy makers should consider both attributes when developing and growing crops and funding those efforts.

Summary: The Complexity of Drought and Solutions to It

The complexity of drought, and the different ways that drought-tolerant crops can respond to it, have several implications for evaluating such crops. First, most information on GE drought-tolerant crops so far comes from greenhouse studies, whose results may be very different from those that will occur when farmers actually grow commercial GE crops.

Second, some crop species are inherently more drought tolerant than others. Many of these species originated in hot and dry climates. Some have also received far less attention from breeders, partly because most are not among the staple crops grown in the temperate climates of developed countries.

Researchers should focus much more effort on improving the agronomic properties and drought tolerance of these crops.

Although important, breeding and genetic engineering are unlikely to substantially increase the productivity of crops faced with severe or extreme drought. And in moderate drought, yields are unlikely to be as high as when water is plentiful. Research on agronomic and agroecological methods that complement drought tolerance is therefore essential.

Finally, the distinction between drought tolerance and WUE is important. Drought-tolerant crops that do not have improved WUE may require as much irrigation as crops that are not drought tolerant.

Chapter 3

The Pipeline of Drought-Tolerant GE Crops

Only one GE drought-tolerant crop is now commercially available: corn (*Zea mays* L.) containing the bacterial *cspB* gene, developed by Monsanto—a variety known as DroughtGard. However, developers have conducted field trials of other GE drought-tolerant crops in the United States.

The first 16 years of commercialized GE crops focused on genes that confer resistance to herbicides or insect pests.[3] DroughtGard offers a new type of GE trait, and is also the first GE variety to address a climate-change related challenge. This product is therefore important not only in its own right, but also to show that the technology can exert a broader effect on agriculture.

Developers of GE crops must adhere to the permitting process of the USDA, which maintains a public database of all field trials. After a developer conducts enough field trials to provide data on a GE crop, the developer submits a petition to the USDA for "deregulation," or regulatory approval, of that variety. The petition includes detailed information on the engineered gene, the effectiveness of the variety, and some of its potential environmental impacts. The USDA uses this information to conduct an environmental assessment, as required by the National Environmental Policy Act.

Both the petition and the assessment are publicly available.[4] For field trials, the USDA does allow the developer to withhold many details, such as the name of an engineered gene, from the public database. However, the public information includes the trait that a gene confers, such as drought tolerance, and the years when trials were conducted.

The most recent five petitions for deregulating new GE varieties required about 34 months, on average, to win USDA approval, and just under five months from the time the agency produced an environmental assessment.[5]

U.S. Field Trials of GE Drought-Tolerant Crops

Beginning in 1998, the number of field trials of GE drought-tolerant crops grew slowly for five or six years. That number then spiked in 2005, and held relatively steady at 80 to 115 trials annually for six years (Figure 2). In 2011, USDA data show 90 field trials for GE drought-tolerant crops through November 14, so the annual total continues to fall within that range. This timeline roughly corresponds to reports that scientists were finding promising genes for drought tolerance through laboratory tests and learning to control their expression (Yang et al. 2010).

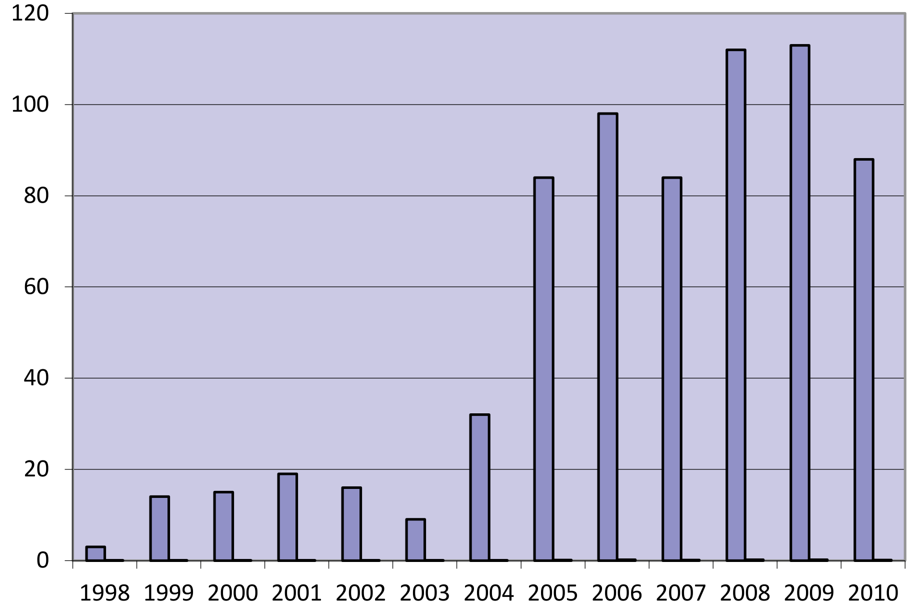
---

[3] Rootworm-resistant *Bt* crops may improve drought tolerance indirectly by preventing damage to corn roots, preserving their ability to take up water. However, that is not the primary purpose of these genes. In other words, this trait does nothing to increase drought tolerance in corn if rootworm is not present. Other means for controlling rootworm also exist, such as chemical insecticides and crop rotation, and several varieties of conventionally bred rootworm-resistant corn have been reported but not yet commercialized.

[4] See *http://www.aphis.usda.gov/biotechnology/not_reg.html.*

[5] The USDA has recently said it would reduce the time required to rule on deregulation petitions to 13 to 15 months. See *http://www.aphis.usda.gov/newsroom/2011/11/customer_driven.shtml.*

Figure 2. USDA-Approved Field Trials of GE Drought-Tolerant Crops, 1998–2010



Source: USDA.

When first introduced into food crops, many of these genes were expressed at high levels all the time (constitutive expression). This trait often hampered crop development, because either the drought-tolerance genes or other genes affected by the expression of those genes caused the plant to grow abnormally.

More recently, scientists have used promoters—parts of a gene that control when, where in the plant, and how strongly it functions—that respond to drought to restrict expression of genes to drought conditions (Umezawal et al. 2006). This important advance has led to hope among scientists working on these crops that new gene combinations will be effective and avoid negative effects on crop growth.

And indeed, the increase in field trials beginning in 2005 suggests a substantial rise in the number of promising GE drought-tolerance genes and promoters. However, the leveling off of field trials since then suggests that further major advances may not have occurred, although other explanations are possible.

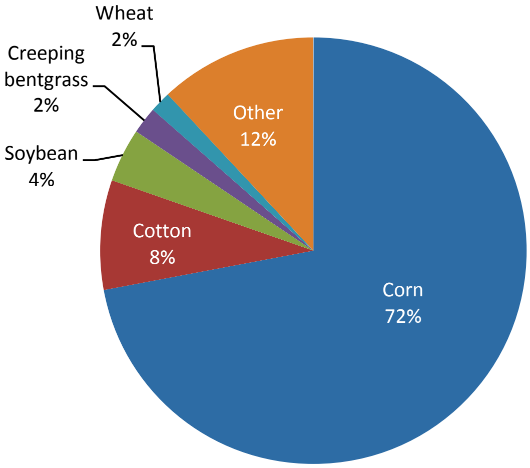
The USDA has granted about 66 percent of total approvals to conduct field trials of GE drought-tolerant crops to Monsanto (418 trials), 8 percent to Pioneer Hi-Bred (50 trials), 5 percent to Rutgers University (31 trials), and 4 percent each to Biogemma and Syngenta (28 and 27 trials, respectively), with the rest spread among other institutions. This analysis shows Monsanto's continuing dominance in developing new biotech traits. These companies and institutions are likely to continue conducting field trials of promising genes for conferring drought tolerance for a number of years.

To limit costs, the developer of an experimental gene and GE crop may initially conduct just a few field trials. Limits on the supply of GE seeds also curb initial testing, as well as some later testing that entails backcrossing the GE crop variety to the latest elite (commercially desired) crop lines. After the early tests, developers may grow different crop varieties with promising genes in more numerous field trials, to test their properties.

Several years also elapse among identification of promising genes, initial crop development, and field trials. In fact, developers typically take 10 to 15 years or more to move GE traits from the early stages to commercialization (Goodman 2002; Goodman and Carson 2000), although recent advances may have shortened this time period somewhat (Phillips McDougall 2011).

The record suggests that several of the GE crops in field trials at mid-decade have now been in development for close to 10 years. These crops should begin to approach commercialization, through petitions to the USDA for deregulation, over the next few years if they are effective and reliable. Most may reach that stage within about seven years.

Figure 3. Top Five Crops in Field Trials of GE Drought-Tolerant Varieties



Source: USDA.

Commercialization of several new crop varieties with effective GE drought-tolerance genes in the next five years would suggest that the technology is promising. However, limited commercialization might suggest that once-promising genes are not as effective in conferring drought tolerance as anticipated. Limited commercialization may also suggest that the predicted profitability of the resulting crop varieties is lower, or that they caused unanticipated problems, such as abnormal growth. If the leveling of field trials for drought tolerance after 2005 reflects a slowdown in the discovery of new genes, this would raise questions about the potential for genetic engineering to meaningfully address drought tolerance in the foreseeable future.

As with earlier GE crops—and as expected from the high costs of developing these crops and the large markets needed to support them—corn, cotton, and soybeans predominate in these field trials (Figure 3). Intellectual property protections and marketing arrangements, such as the inability of growers to save seed from year to year for non-hybrid crops, have allowed the genetic engineering industry to capture substantial profits from these earlier GE crops. The distribution of field trials may also reflect the especially high profitability of corn seed.

The small number of field trials of large-acreage crops such as wheat and rice, despite potentially large markets, may reflect international controversy and lack of acceptance of genetically engineered crops among several U.S. trading partners. The ability of growers in some countries to continue to save seed from their crops for planting the following year could restrict developers' returns on the sizable investment required to create these crops.

Field Trials of GE Crops with Improved Water-Use Efficiency

The biotech industry has claimed that GE crops can contribute to the sustainability of agriculture by using less water. For example, Monsanto has said that it intends to produce "more crop per drop"—a phrase that strongly suggests that GE crops will use water more efficiently than other crops. A Monsanto press release specifically mentions improving WUE, and refers to the large percentage of freshwater used by agriculture, and the need to use it more efficiently (Monsanto 2010).

Contrary to industry statements, however, the USDA database shows only nine approved field trials for several crops genetically engineered to use water efficiently, all since 2006. This very small number suggests that using genetic engineering to improve WUE—independent of drought tolerance—is not an important focus of the biotech industry, or that such efforts have been unsuccessful. And because, as noted, improved drought tolerance typically does not mean improved water-use efficiency, there is no assurance that GE crops with more drought tolerance will also have better WUE.

Seed companies could be using conventional and marker-assisted breeding programs to improve WUE—efforts that would not show up in the USDA database. Conventional breeding for WUE might actually be more practical, as seeds with that trait might not be as profitable for seed companies, and the conventional approach to developing them avoids the extra time and cost of winning regulatory approval for GE crops.

Monsanto's Drought-Tolerant Corn: The Bacterial Cold-Shock Gene

Monsanto's DroughtGard, which received regulatory approval in December 2011, contains a "cold-shock gene" derived from bacteria. The gene, *cspB*, comes from the common soil bacterium *Bacillus subtilis* (Castiglioni et al. 2008). The gene is one of a number of similar genes found in bacteria that code for proteins that appear to stabilize mRNA—the molecules that code for protein in all organisms—under stresses such as low temperatures (Chaikam and Karlson 2010).[6]

A plant actin promoter ensures that virtually all plant tissues produce relatively large amounts of the *cspB* protein virtually all the time (constitutive expression).[7] This pattern is similar to that in most previously commercialized GE crops. However, scientists are combining many other candidate genes for drought tolerance with promoters that express the genes primarily during drought (although expression might also occur under some unpredicted conditions, and is not easy to track) (see Chapter 4).[8]

Evaluating DroughtGard's Effectiveness

As noted, measuring drought tolerance is challenging. Monsanto's petition to the USDA cites results from two growing seasons of field trials in several locations in the United States and Chile that faced

---

[6] Stresses such as freezing or desiccation from drought can alter molecules in plant cells, such as RNA. For example, desiccation can interfere with the structure and function of such molecules by reducing the amount of water in a cell that would otherwise stabilize their structure.

[7] The promoter is the part of the gene that controls when and in what parts of the plant the gene functions, and how often the gene is turned on, or expressed.

[8] Although cold-shock proteins such as CspB from *B. subtilis* are not found in plants, other proteins called cold-shock-domain proteins are. These contain a section, or domain, that is very similar to bacterial cold-shock proteins. The cold-shock-domain proteins appear to serve several functions, although they are not completely understood (Karlson and Imai 2003). Recent research suggests a role for some plant cold-shock-domain proteins in crop development and adaptation to cold (Kim, Sasaki, and Imai 2009; Park et al. 2009).

varying levels of water availability, which is a consequence of drought. Company scientists measured drought through the amount of moisture in soil, and compared the crop's growth response with that of conventional commercial varieties of corn grown in regions where the tests were performed.

Monsanto reported a reduction in losses expected under moderate drought of about 6 percent, compared with non-GE commercial corn varieties, although there was considerable variability in these results (Reeves et al. 2010). That means that farmers using Monsanto's *cspB* corn could see a 10 percent loss of yield rather than a typical 15 percent loss under moderate drought—or an increase of about 8 bushels per acre, based on a typical 160-bushel non-drought yield.

Monsanto also reported an improvement of 11 percent to 20 percent in the 50 percent loss of yield in control plants under severe drought (Castiglioni et al. 2008). Given a typical non-drought yield of 160 bushels per acre, that means the GE crop would improve yield by 9 to 16 bushels per acre under these conditions. Losses compared with average national yields would therefore be about 40 to 44 percent under severe drought, based on these preliminary data. However, in assessing Monsanto's *cspB* corn, the USDA asserts that it is effective primarily under moderate, not severe, drought conditions. This may be because, although Monsanto's product may provide some protection, losses would remain very high. Droughts can also be extreme or exceptional, surpassing the intensity of severe droughts. Monsanto's *cspB* corn is unlikely to have any benefit under extreme drought conditions.

Monsanto's tests provide a valuable initial approximation of the protection against drought that *cspB* gives the crop under limited test conditions. However, the tests do not accurately measure the drought tolerance the gene can offer under a range of possible conditions, including droughts of varying timing, intensity, and duration, as well as varying ambient temperatures and soil conditions. The high variability in the test results showed that for several tests, Monsanto's corn did not provide a statistically significant improvement in yields under drought conditions.

Market Uncertainties

Monsanto based its petition for deregulation on field tests conducted in 2006 and 2007, although the company probably continued these tests in later years. In these field tests, the company compared *cspB* corn only to commercial varieties of corn available at the time. However, because breeders have been steadily improving the drought tolerance of conventionally bred corn (Araus et al. 2008), Monsanto's tests will be out of date when *cspB* corn is commercialized—several years after the reported field tests.

Agronomists may test promising experimental varieties of crops in addition to commercialized varieties (Iowa State University 2011; University of Illinois 2010, University of Maryland 2010; Martin et al. 2005). Including other experimental drought-tolerant corn varieties that may reach commercial use in Monsanto's field tests may have provided a more accurate assessment of the value of *cspB* corn (although not all experimental varieties are eventually commercialized).

Several seed companies have recently announced experimental drought-tolerant corn varieties developed through conventional breeding (Bennett 2011; Syngenta 2011). These companies claim that the drought tolerance of these varieties is similar to or greater than that of *cspB* corn, although the companies have disclosed few details to support these claims. Public-sector crop breeders in the United States have also announced several new conventional drought-tolerant varieties (Carena et al. 2009).

One recent study estimated that the drought tolerance of conventional crops has increased by about 1 percent per year over the past several decades (Yu and Babcock 2010), although due to the difficulty in accurately measuring drought tolerance, this value should be viewed as a rough estimate. This analysis suggests that the drought tolerance of conventional corn will be about 5 or 6 percent higher in 2012 than when Monsanto performed its tests. Increases in drought tolerance provided by *cspB* corn could therefore be considerably lower than Monsanto has projected, given these recent improvements in conventional varieties.

This phenomenon, known as "yield lag," can occur with any new crop trait, conventional or transgenic. Because Monsanto is likely to have crossed *cspB* into elite commercial varieties, yield lag may be minimal. Still, new conventionally bred drought-tolerant corn varieties other than *cspB* may well come to market and compete with Monsanto's varieties, and boost overall corn yield under drought.

On the other hand, Monsanto performs conventional breeding as well as genetic engineering. Adding the *cspB* gene to the best new conventional drought-tolerant varieties could provide even greater drought resistance. Transferring an engineered gene to newer corn varieties, which requires at least several rounds of breeding (recurrent backcrossing), could take several years. However, the company could develop such newer varieties quickly because commercial corn varieties are hybrid, and the company could change the parent plant line that does not contain *cspB* from year to year. Monsanto could then quickly cross this parent line with the line containing *cspB* to produce new commercial drought-tolerant hybrid varieties.

Farmers usually do not know whether they will face drought the following season when they are buying seed. GE drought-tolerant seed is also very likely to cost more than non-engineered seed, as is the case with seed for crops with other GE traits. And because *cspB* corn is of limited value in severe or extreme drought, farmers are unlikely to use it widely used under those conditions.

These drawbacks may restrict the market for *cspB* corn seed to regions where moderate drought is most likely to occur, such as western parts of the U.S. Corn Belt. In its environmental assessment of *cspB* corn, the USDA suggests that farmers will not widely grow it on the 85 percent of U.S. corn acres that typically receive adequate moisture through precipitation (USDA 2011d). Corn containing *cspB* will likely be largely restricted to the remaining 15 percent, as well as markets abroad with similar climates. Still, high corn prices (USDA 2011a), as now prevail in both national and global markets, will encourage farmers to maximize productivity, and may increase the market for *cspB* corn.

Other considerations in the purchase of *cspB* corn include the yield, pest resistance, and other traits of the crop varieties that contain the gene. Potential agreements between seed companies for cross-licensing traits and varieties will also affect the market, if such agreements do not violate antitrust laws. Such agreements could mean that other companies use Monsanto's *cspB* to produce other corn varieties, which could increase the acreage planted with *cspB* corn.

Given all these factors, several years of commercialization will likely be needed to determine how *cspB* corn performs in the market compared with conventional drought-tolerant corn.

Unintended Negative Effects

A particular gene or GE trait often has multiple effects on a crop, because engineered genes and their products—RNA and proteins—affect a plant's biochemistry in complex and often unpredictable ways. This is known in genetics as pleiotropy. These effects can curb crop growth, such as by making the crop more susceptible to diseases, and crop quality, including the amount of nutrients, anti-nutrients, and toxicants in food. Several examples of pleiotropy have occurred in breeding (National Research Council 2004) as well as genetic engineering (Zeller et al. 2010; Poerschmann et al. 2005).

In its deregulation petition, Monsanto noted no undesirable effects of the *cspB* gene and its expressed protein on the growth of DroughtGard corn, including crop yield, given adequate moisture. Lower yield under adequate moisture is perhaps the most common undesirable trait associated with conventional drought tolerance.[9]

However, pleiotropy may occur only under certain conditions, so it could show up under widespread commercial cultivation even if it does not occur during field trials. For example, the engineered drought-tolerance gene *era1* may make a plant more susceptible to several pathogens (Goritschnig et al. 2008; Wang et al. 2005). This could curb yield significantly if the pathogens are present, the plant has no other mechanisms to resist them, and environmental conditions are conducive to disease.

Several years of extensive commercial use of *cspB* corn—and possibly longer if the crop is not monitored—will be needed to determine with some certainty whether any such undesirable pleiotropy occurs.

Water-Use Efficiency of cspB *Corn*

As Chapter 2 noted, greater drought tolerance typically does not mean better water-use efficiency. To have improved WUE, *cspB* corn would need to require less water to produce normal yields.

Monsanto's petition for deregulation compares the yield of *cspB* corn with that of other commercial corn varieties under various levels of water availability (Reeves et al. 2010). Based on these limited data, *cspB* corn does not appear to require less water than corn varieties already on the market to produce normal yields.

More to the point, the petition does not provide data on water use per unit of production, and therefore no information is available to support higher WUE for *cspB* corn. The petition recognizes the importance of water use efficiency at several points (Reeves et al. 2010: 85, 252), but also notes that *cspB* corn does not differ from conventional corn in water use.

Summary: Monsanto's *cspB* Corn and the GE Drought-Tolerance Pipeline

If DroughtGard is competitive with other drought-tolerant corn varieties likely to enter the market soon, and negative pleiotropy proves to be of little consequence, the variety could make a small to modest contribution to reducing crop losses from drought.

---

[9] Yield drag is typically associated with genes near the desired gene that are transferred with it during breeding, rather than with pleiotropy.

Success, even if limited, would mark a milestone in the development of GE crops. However, for drought-tolerant GE corn to distinguish itself, it must reach several other milestones. These include showing that genetic engineering can have a substantial impact on drought tolerance, and that drought-tolerant varieties can compete in the field and on the market with non-GE drought tolerant varieties and better farming practices.

Given the seven years since the sharp rise in field trials of GE drought-tolerant crops, we should expect at least several new ones to emerge from the pipeline to commercialization in the next few years. The rate at which these appear should shed light on whether this phase of genetic engineering technology can provide effective genetically and physiologically complex traits.

If poor farmers in parts of the world most affected by drought find GE varieties useful, those varieties will have made a useful contribution to the world's plant-breeding repertoire. However, moving a single major gene derived from midwestern U.S. germplasm into crop varieties adapted to drought-stressed environments around the world will likely take at least 15 years of development and testing for each such environment.

Chapter 4

Prospects for GE Drought-Tolerant Crops

Proponents of genetic engineering often cite improved drought tolerance as an important benefit of the technology. This confidence is primarily based on the pipeline of experimental GE drought-tolerant crops, as cited in the scientific literature and field trials in the United States and other countries.

However, the prospects of experimental crops warrant some caution, for several reasons. In their review of GE drought-tolerant genes and crops, Yang et al. (2010) find that the majority of such crops have been tested only in controlled conditions, such as greenhouses. As they note, and as Chapter 3 also noted, scientists cannot accurately predict the efficacy of those crops based on such conditions, owing to the complexity of drought and the environment.

For example, a transcription factor gene from Monsanto, *NF-YB*, improved yield by about 50 percent, compared with non-GE crops, under drought conditions one year (for a 28 percent reduction in yield compared with normal conditions), and by 20 percent another year (Nelson 2007). However, later field studies found only a 10 percent to 15 percent increase in yield under various drought conditions (Pennisi 2008). Results of tests of experimental GE drought-tolerant crops in both greenhouses and field trials should therefore be considered preliminary, and could ultimately be revised considerably.

Yang et al. (2010) also note that experimental crops have often shown negative pleiotropy, seriously affecting growth and yield. The authors attribute these negative properties to the constitutive expression of these genes: the fact that they are turned on all the time. In more advanced varieties, plant promoters apparently turn on these drought-tolerance genes only during drought. Based on these advances, the authors express confidence in the prospects of many of these genes.

However, genes expressed only under the stress of drought might reduce but not eliminate significant pleiotropy, as droughts typically continue for weeks or longer. Depending on the stress levels that stress-specific promoters require to activate gene expression, and the timing of drought, these genes could still have significant negative effects. For example, if drought occurs early in the growth of a crop and lasts for a considerable time, it could still undermine plant development.

Can Genetic Engineering Based on Single Genes Succeed?

Many genes or alleles (gene variants) control the drought tolerance that already exists in crops, and they may vary in their effectiveness depending on their specific combinations and environmental conditions. These properties have raised questions about whether scientists can confer effective drought tolerance by manipulating only one or a few genes, as they are now limited to doing through GE.

Single genes can affect complex traits such as drought tolerance in several ways. Several groups of scientists are exploring one class of genes with multiple effects: transcription factors (Saibo, Lourenco, and Oliveira 2009; Century, Reuber, and Ratcliffe 2008). These proteins can affect the expression of several other genes, and multiple aspects of plant metabolism. Some transcription factors are associated with drought tolerance.

Scientists have also long considered another class of genes for their potential to reduce drought stress: osmotic protectants, which can improve the water balance in plant tissues. Genes that code for enzymes that produce osmotic protectants have protected crops from drought in some experiments, although they have not yet had commercial success (Yang et al. 2010).

Other genes produce proteins that may affect crop metabolism significantly, including by reducing drought stress. C*spB* and *era1* both affect the structure or function of many aspects of plant function. The *era1*drought-tolerance trait contains a mutated version of a gene that normally alters the function of many proteins in the plant by modifying their chemical makeup and structure (Wang et al. 2009; Wang et al. 2005). These modified proteins include some involved directly or indirectly with drought tolerance and disease resistance.

Thus, many single genes have evolved to affect the function of many other genes or proteins, and these single genes can alter the function of complex traits such as drought tolerance. However, as noted, many of these genes may also alter other crop traits, producing pleiotropy.

Using Drought-Tolerance Genes from Plants

The first generation of GE crops contained genes from bacteria, such as *Bacillus thuringiensis (Bt)*, which provided resistance to some insect pests, or *Agrobacterium tumifaciens*, which provided the gene for resistance to the herbicide glyphosate (Padgette et al. 1995)**.** These genes were typically expressed from strong constitutive promoters (those that are always turned on), such as from plant viruses (especially the cauliflower mosaic virus 35S promoter) (Fang et al. 1989).

These genes did not require intricate, multiple connections with plant genes or plant proteins to function. For example, *Bt* genes produce toxins that kill pest insects directly. And the glyphosate tolerance gene is an enzyme that converts one compound to another, as part of a process that makes amino acids produced by both plants and bacteria. This gene does not interact in especially complex ways with other genes or proteins.

However, many, if not most, of the genes scientists are now considering for engineering drought tolerance, such as transcription factors, are from plants—often crop plants—and are expressed using plant promoters.[10] Scientists are taking this approach because these genes have evolved specific interactions with the many crop genes that they affect, such as drought-tolerance genes. Genes from distantly related organisms such as bacteria and animals usually have not evolved the same specific interactions.

Still, breeding efforts and genetic studies have often found that the effectiveness of crop genes associated with drought tolerance varies in different environments—called low heritability. The effectiveness of such genes can also vary among crop varieties—known as genetic context effect, or background heritability (Cattivelli et al. 2008; Dekkers and Hospital 2002). For genetically complex traits such as drought tolerance, each gene contributes a limited share of the protective effect.[11]

---

[10] The *cspB* gene, from the bacterium *Bacillus subtilis*, is an exception, although its promoter is from a plant.

[11] The genes—or more commonly the regions on plant chromosomes where yet-to-be-identified genes are located—are called quantitative trait loci, or QTL.

This raises questions about whether some of the genes used in genetic engineering will also have low heritability in different environments, or genetic context effects in different crop varieties or crops. Because scientists have tested most of these genes in the environment only to a limited extent, or in just a few crop varieties, the answer must await further experimentation.

Conventional breeding—especially methods based on genomic science, such as marker-assisted selection and ideotype breeding (matching several complementary traits)—may overcome some of the heritability limitations of drought-tolerance genes by combining several in a single crop variety. However, even in those cases, many genes that improve drought tolerance during one kind of drought may not be useful in other drought environments.

Because scientists cannot now engineer multiple genes, genetic engineering may face greater challenges if some plant-derived drought-tolerance genes have low heritability. The use of mini-chromosomes or a similar technique to engineer multiple genes may eventually help overcome such limitations (Yu, Han, and Birchler 2007). However, while promising, such techniques may take decades before producing varieties that reach farmers' fields.

Costs, Markets, and the Time Required to Develop GE Crops

Using genetic engineering to produce certain traits is usually much more costly than relying on conventional breeding. The price of seeds must typically include these development costs if companies are to make a profit.

However, seed companies cannot sell crop varieties with these traits for more than they are worth to farmers, unless they are subsidized. In a competitive market, that could give conventionally bred drought-tolerant crops an advantage over GE crops—unless the latter are more effective by an amount that compensates farmers for their higher initial costs.

Industry-sponsored studies put the average cost of developing a GE trait at $136 million (Phillips McDougall 2011**).** Goodman (2002) puts the average cost of developing a trait through conventional breeding at $1 million.

Some have attributed the high cost of genetic engineering to regulatory requirements. However, regulations are unlikely to account for most of the costs of developing GE crops. No estimates of such costs based on public data are available. However, one estimate based on company data suggests that regulatory costs for developing a GE crop range from $6.2 million to $15.4 million across 10 major countries (Kalaitzantonakis 2007).

More recently, one company put average regulatory costs for GE crops at $35.1 million—about 26 percent of total development costs (Phillips McDougall 2011) (or 4.5 percent to 11 percent, given the cost estimates of Kalaitzandonakes, Alston, and Bradford 2007). If these numbers are accurate, they suggest that most of the costs of producing GE crops reflect research and development and other business expenses rather than regulatory costs.

Proponents of genetic engineering have suggested that scientists can use the technology to develop new traits much faster than when they use breeding. However, both genetic engineering and conventional breeding typically take 10 to 15 years to develop a trait (Goodman 2002; Goodman and Carson 2000).

Although regulatory requirements can add some time to the development of GE crops, much of the required time stems from other needed steps, such as field trials to assess the function of new genes over several years, and efforts to backcross engineered genes into desirable crop varieties.

Today scientists randomly insert engineered genes into different chromosomal sites for each independently engineered variety, producing unpredictable expression. Field trials are essential for examining how this expression plays out. The tissue culture process used in engineering crops also introduces random mutations in the plant, requiring field tests to check for unintended negative properties.

Technological advances may reduce the time required to bring GE crops to market after promising genes are discovered. For example, the ability to directly engineer elite (desirable) crop varieties could reduce or avoid the need to transfer genes from an original engineered variety to elite varieties through breeding—a time-consuming process (Nelson et al. 2007; Shewry and Jones 2005; Breitler et al. 2004; Ko et al. 2003). Scientists could also combine this approach with other new methods, such as the use of zinc-finger nucleases to insert genes into desired locations in a crop genome (Durai et al. 2005). None of these advances, however, would reduce the time required to develop and test the initial engineered variety for new expression patterns, and for unintended negative effects from the new gene.

A pilot program of the USDA's Federal Crop Insurance Corp. has reduced insurance premiums for farmers who grow some GE crop varieties that are resistant to multiple insects and herbicides—a program that effectively subsidizes those varieties (USDA 2011c).[12] If such subsidies are also available for GE drought-tolerant varieties, especially if they also have other GE traits, the market for them could grow. However, conventionally bred drought-tolerant corn varieties may also qualify for such support.

Lower costs for labor and other inputs have been major selling points for previous GE crops (Fernandez-Cornejo and Caswell 2006). Herbicide-tolerant crops initially required fewer herbicides and applications, and allowed more flexible spray schedules. Insect-resistant crops such as *Bt* corn reduce the costs of spraying. However, GE drought tolerance does not reduce the time or labor required to manage crops.

Whether farmers will grow GE drought-tolerant corn on enough acres to make it profitable for its developers therefore depends on a number of factors whose outcome is unclear. Overall, the higher development costs of GE varieties mean that they must be more effective than other varieties to be competitive.

---

[12] This program was set to expire at the end of calendar year 2011.

Chapter 5

Conclusions and Recommendations

About 16 years after developers first commercialized crops genetically engineered for herbicide tolerance and insect resistance, only one drought-tolerant GE crop has been approved for commercialization. This may reflect the greater complexity of engineering crops that are drought tolerant.

The scientific literature suggests that scientists have resolved several major obstacles to GE drought tolerance in the past 10 years. These include finding single genes, such as plant transcription factors, that may improve the drought tolerance of crops despite its genetic complexity, and learning to control the function of these genes more precisely, to reduce the possibility that they will interfere with crop development.

However, most studies of these crops have occurred under controlled conditions, which cannot replicate the complexity of drought in the field. How effective these crops will actually be—and whether unintended negative effects may occur when drought-tolerance genes turn on during drought—therefore remain unclear.

Advances in the technology of GE drought tolerance correspond with a dramatic increase in the number of USDA-approved field trials of such crops beginning in 2005—to about 80 to 100 per year. However, the number of field trials has remained roughly the same for the past seven years, suggesting that scientists may have discovered few additional drought-tolerance genes during that time.

If so, GE drought-tolerant crop varieties now in the pipeline may represent the bulk of such products that will appear in the coming decade or longer. That is especially the case because new GE crops typically take about 10 to 15 years to reach commercialization, and initial research precedes field trials by a few years. For this phase of the technology to succeed, several effective new varieties should arrive on the market over the next seven years.

In the interim, the drought tolerance of corn produced through conventional breeding and better agronomy has been improving for several decades. Several recent examples from independent organizations, universities, and companies show that this trend is continuing, and may even be increasing.

The drought tolerance of other crops, including sorghum, cassava, rice, wheat, and pearl millet, is also improving. Whether all the new varieties are available commercially, and the level of drought tolerance they provide, is unclear. However, this record suggests substantial promise for the use of conventional breeding to improve the drought tolerance of these and other crops.

Scientists have reported that several crops native to hot and dry parts of the Southern Hemisphere, such as sorghum, millets, cassava, and cowpea, have inherent drought tolerance higher than most crops from countries with temperate climates. Breeding programs have generally neglected these orphan crops, so they are often not as productive as more well-known crops under favorable conditions. Researchers could likely make relatively rapid progress in addressing these disparities with adequate effort, which these crops deserve.

Monsanto's DroughtGard, which contains the bacterial *cspB* cold-shock gene, reduces losses during moderate drought by about 6 percent. This corn has little benefit in more severe drought or extreme droughts, and none under adequate water availability. Information on the efficacy of *cspB* corn should also be considered preliminary, because of the variability of drought and only two years of publically available field trial data.

One recent study found that breeding increased drought tolerance of corn by an average of 1 percent per year. This finding may be only a rough estimate, because of the difficulty of measuring drought tolerance. However, it suggests that *cspB* corn provides only about one-third to one-half the drought tolerance expected from conventional breeding during the 10-to-15-year timeframe for developing new GE traits if *cspB* corn is planted on most corn acres. An annual increase in drought tolerance of just 0.3 to 0.4 percent over 10 to 15 years through conventional breeding would provide the same level of benefits provided by *cspB* corn.

In fact, farmers are not expected to plant *cspB* corn on most corn acres in the United States. If *cspB* corn provides a 6 percent reduction in yield loss on the 15 percent of U.S. corn acres typically affected by moderate drought, as suggested by Monsanto's petition for deregulation and the USDA's environmental assessment, corn productivity would increase by about 1 percent nationwide. That is about the same as the average increase achieved by conventional breeding and agronomy per year, as determined by the study noted above.

Although the biotech industry has suggested that it will also improve water-use efficiency, *cspB* does not appear to bolster that trait. In fact, the very small number of fields trials of crops with improved WUE over the past two decades strongly suggests that the industry has not made that trait a priority—or that scientists have found only a few genes that affect it, or that those genes are not effective enough.

The commercial success of *cspB* corn depends on several factors that remain uncertain—including how well it will compete on effectiveness and cost with new conventionally bred drought-tolerant corn varieties, and how many farmers will find uses for it.

Recommendations

In light of the current state of R&D on GE drought tolerance, and challenging questions about the overall prospects for commercially viable GE drought-tolerant crops, we recommend that:

- Congress and the USDA should substantially increase support for public crop-breeding programs to improve drought tolerance. Because large seed companies focus mainly on engineered crops, this would give farmers better access to non-GE drought-tolerant varieties.

- Congress and the USDA should use conservation programs funded under the federal Farm Bill to expand the use of available methods for improving drought tolerance and WUE. These include the use of water-conserving irrigation equipment, which may require considerable investment on the part of farmers, and farming methods that increase soil organic matter, which farmers must consistently use over several years to see substantial benefits. The Farm Bill can offer incentives or subsidies to help farmers at risk of drought adopt such practices.

- The USDA and public universities should increase research devoted to finding better ways to store and conserve soil, groundwater, and surface water, and better farming methods to withstand drought.

- Public and private research institutions should devote more funding and effort to crops that are important in drought-prone regions in the Southern Hemisphere. These crops, which include sorghum, pearl millet, cassava, and cowpeas, are inherently more drought-tolerant than crops familiar in the Northern Hemisphere.

- Researchers at the USDA and public universities should carefully monitor the efficacy and possible undesirable effects of *cspB* corn. Such monitoring is important because this variety is the first GE commercial drought-tolerant crop, and the resulting information would enhance our understanding of GE drought tolerance. Similar monitoring should occur for any other GE drought-tolerant crops.

- The USDA and public universities should expand their research on using plant breeding to improve water use efficiency—a vital concern that has not attracted major efforts from the biotechnology industry. The public sector should also invest in improving water-saving irrigation methods and the water-holding capacity of soil, reducing water loss from soil, and developing better water storage facilities.

References

Araus, J.L., G.A. Slafer, M.P. Reynolds, and C. Royo. 2002. Plant breeding and drought in C3 cereals: What should we breed for? *Annals of Botany* 89:925–940.

Araus, J.L., G.A. Slafer, C. Royo, and M.D. Serret. 2008. Breeding for yield potential and stress adaptation in cereals. *Critical Reviews in Plant Science* 27:377–412.

Bennett D. 2011. Agribusiness: Pioneer releases drought-tolerant corn hybrids. *Delta Farm Press*. Online at *http://deltafarmpress.com/corn/agribusiness-pioneer-releases-drought-tolerant-corn-hybrids?page=1*.

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research* 112:119–123.

Blum, A. 1996. Crop responses to drought and the interpretation of adaptation. *Plant Growth Regulation* 20: 135–148.

Brady, N.C., and R.R. Weil. 2008. *The nature and properties of soils,* 14th ed. Columbus, OH: Pearson/ Prentice Hall.

Breitler J.C., D. Meynard, J. Van Boxtel, M. Royer, F. Bonnot, L. Cambillau, and E. Guiderdoni. 2004. A novel two T-DNA binary vector allows efficient generation of marker-free transgenic plants in three elite cultivars of rice (*Oryza sativa L.*). *Transgenic Research* 13:271–287.

Calzadilla, A., K. Rehdanz, and R.S.J. Tol. 2010. The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. *Journal of Hydrology* 384(3–4):292–305.

Carena M.J., G. Bergman, N. Riveland, E. Eriksmoen, and M. Halvorson. 2009. Breeding maize for higher yield and quality under drought stress. *Maydica* 54:287–296.

Castiglioni, P., D. Warner, R.J. Bensen, D.C. Anstrom, J. Harrison, and M. Stoecker et al. 2008. Bacterial RNA chaperones confer abiotic stress tolerance in plants and improved grain yield in maize under water-limited conditions. *Plant Physiology* 147:446–455.

Cattivelli L., F. Rizza, F-W. Badeck, E. Mazzucotelli, A.M. Mastrangelo, E. Francia, C. Mare, A. Tondelli, and A.M. Stanca. 2008. Drought tolerance improvement in crop plants: An integrated view from breeding to genomics. *Field Crops Research* 105:1–14.

Century K., T.L. Reuber, and O.J. Ratcliffe. 2008. Regulating the regulators: The future prospects for transcription-factor-based agricultural biotechnology products. *Plant Physiology* 147:20–29.

Chaikam, V., and D.T. Karlson. 2010. Comparison of structure, function and regulation of plant cold shock domain proteins to bacterial and animal cold shock domain proteins. *BMB Reports* 43(1):1–8.

CIMMYT (International Maize and Wheat Improvement Center). No date. Maize farmers and seed businesses changing with the times in Malawi. Online at *http://www.cimmyt.org/index.php/en/about-us/media-resources/newsletter/715-maize-farmers-and-seed-businesses-changing-with-the-times-in-malawi*.

Collins, N.C., F. Tardieu, and R. Tuberosa. 2008. Quantitative trait loci and crop performance under abiotic stress: Where do we stand? *Plant Physiology* 147:469–486.

Dekkers J.C.M., and F. Hospital. 2002. The use of molecular genetics in the improvement of agricultural populations. *Nature Reviews Genetics* 3:22–32.

Durai S., M. Mani, K. Kandavelou, J. Wu, M.H. Porteus, and S. Chandrasegaran. 2005. Zinc finger nucleases: custom-designed molecular scissors for genome engineering of plant and mammalian cells. *Nucleic Acids Research* 33(18):5978–5990.

Edmeades, G.O., J. Bolanos, S.C. Chapman, H.R. Lafitte, and M. Banziger. 1999. Selection improves drought tolerance in tropical maize populations: Gains in biomass, grain yield, and harvest index. *Crop Science* 39: 1306–1315.

Fang R-X., F. Nagy, S. Sivasubramaniam, and N-H. Chua. 1989. Multiple *cis* regulatory elements for maximal expression of the cauliflower mosaic virus 35S promoter in transgenic plants. *Plant Cell* 1:141–150.

Food and Agriculture Organization (FAO). 1996. The world sorghum and millet economies: Facts, trends and outlook. Rome. Online at *http://www.fao.org/docrep/W1808E/w1808e01.htm.*

Fernandez-Cornejo, J., and M. Caswell. 2006. The first decade of genetically engineered crops in the United States. EIB-11. Washington, DC: USDA, Economic Research Service.

Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil & Tillage Research* 66:197–205.

Garris, A.J., T.H. Tai, J. Coburn, S. Kresovich, and S. McCouch. 2005. Genetic structure and diversity in *Oryza sativa* L. *Genetics* 169:1631–1638.

Goodman, M.M. 2002. New sources of germplasm: Lines, transgenes, and breeders. In J.M. Martinez, F. Rincon, and G. Martinez, eds., *Memoria congresso nacional de fitogentica* (Saltillo, Mexico: University Antonimo Agric. Antonio Narro).

Goodman, M.M., and M.L. Carson. 2000. Reality vs. myth: Corn breeding, exotics, and genetic engineering. *Annual Corn Sorghum Research Conference Proceedings* 55:149–172.

Goritschnig, S., T. Weihmann, Y. Zhang, P. Fobert, P. McCourt, and X. Li. 2008. A novel role for protein farnesylation in plant innate immunity. *Plant Physiology* 148:348–357.

Gurian-Sherman, D. 2009. Failure to yield: Evaluating the performance of genetically engineered crops. Cambridge, MA: Union of Concerned Scientists.

Gurian-Sherman, D., and N. Gurwick. 2009. No sure fix: Prospects for reducing nitrogen fertilizer pollution through genetic engineering. Cambridge, MA: Union of Concerned Scientists.

Harris, K, P.K. Subudhi, A, Borrell, D. Jordan, D. Rosenow, H. Nguyen, P. Klein, R. Klein, and J. Mullet. 2007. Sorghum stay-green QTL individually reduce post-flowering drought-induced leaf senescence. *Journal of Experimental Botany* 58(2):327–338.

Headey, D., and S. Fan. 2008. Anatomy of a crisis: the causes and consequences of surging food prices. *Agricultural Economics* 39 (suppl.):375–391.

Heim, R.R., Jr. 2002. A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society of the United States*, August.

IITA. 2008. Farmers get better yields from new drought-tolerant cassava. Ibadan, Nigeria. Online at *http://old.iita.org/cms/details/news_details.aspx?articleid=1897&zoneid=81*.

Iowa State University. 2011. Corn report. Ames, IO. Online at *http://www.croptesting.iastate.edu/corn/reports.php.*

Jiang, Y. 2009. China's water scarcity. *Journal of Environmental Management* 90:3185–3196.

Kalaitzandonakes, N., J.M. Alston, and K.J. Bradford. 2007. Compliance costs for regulatory approval of new biotech crops. *Nature Biotechnology* 25(5):509–511.

Karlson, D., and R. Imai. 2003. Conservation of the cold shock domain protein family in plants. *Plant Physiology* 131:12–15.

Kim, M.H., K. Sasaki, and R. Imai. 2009. Cold shock domain protein 3 regulates freezing tolerance in *Arabidopsis thaliana*. *Journal of Biological Chemistry* 284:23454–23460.

Ko, T-S., S. Lee, S. Krasnyanski, and S.S. Korban. 2003. Two critical factors are required for efficient transformation of multiple soybean cultivars: Agrobacterium strain and orientation of immature cotyledonary explant. *Theoretical and Applied Genetics* 107:439–447.

Kratochvil, R.J., P. Forrestal, M. Islam, and P. Watkins. 2010. Maryland corn hybrid performance tests. College Park, MD: University of Maryland. 2010. Online at *http://www.mdcrops.umd.edu/corn/2010%20Agronomy%20Facts%2054%20Final%2011-14-10.pdf.*

Liu, K., M. Goodman, S. Muse, J.S. Smith, E. Buckler, and J. Doebley. 2003. Genetic structure and diversity among maize inbred lines as inferred from DNA microsatellites. *Genetics* 165: 2117—2128.

Long, S.P., and D.R. Ort. 2010. More than taking the heat: crops and global change. *Current Opinion in Plant Biology* 13:241–248.

Lotter, D.W., R. Seidel, and W. Liebhardt. 2003. The performance of conventional and organic cropping systems in an extreme climate year. *American Journal of Alternative Agriculture* 18(2):1–9.

Martin, K.L, P.J. Hodgen, K.W. Freeman, R. Melchiori, D.B. Arnall, R.K. Teal, R.W. Mullen et al. 2005. Plant-to-plant variability in corn production. *Agronomy Journal* 97:1603–1611.

Monsanto. 2010. Increasing "crop per drop" critical, says Monsanto's Fraley, adoption of sustainable agriculture key to meeting demands of hungry, growing world. St. Louis, MO. Online at *http://monsanto.mediaroom.com/index.php?s=43&item=834.*

National Research Council. 2008. *Lost crops of Africa,* vol. 3: *Fruits*. Washington, DC: National Academies Press.

National Research Council. 2006. *Lost crops of Africa,* vol. 2: *Vegetables*. Washington, DC: National Academies Press.

National Research Council. 2004. *Safety of genetically engineered foods: Approaches to assessing unintended health effects*. Washington, DC: National Academes Press.

National Research Council. 1996. *Lost crops of Africa,* vol. 1: *Grains*. Washington, DC: National Academies Press.

Nelson, D.E., P.P. Repetti, T.R. Adams, R.A. Creelman, J. Wu, D.C. Warner et al. 2007. Plant nuclear factor Y (NF-Y) B subunits confer drought tolerance and lead to improved corn yields on water-limited acres. *Proceedings of the National Academy of Sciences* 104(42):16451–16455.

Padgette, S.R., K.H. Kolacz, X. Delannay, D.B. Re, B.J. LaVallee, C.N. Tinius, W. Rhodes, Y. I. Otero, G.F. Barry, D.A. Eichholtz, V.M. Peschke, D.L. Nida, N.B. Taylor, and G.M. Kishore. 1995. Development, identification, and characterization of a glyphosate-tolerant soybean line. *Crop Science* 35:1451–1461.

Park, S. J., K.J. Kwak, T.R. Oh, Y.O. Kim, and H. Kang, H. 2009. Cold shock domain proteins affect seed germination and growth of *Arabidopsis thaliana* under abiotic stress conditions. *Plant Cell Physiology* 50: 869–878.

Pennisi, E. 2008. The blue revolution, drop by drop, gene by gene. *Science* 320:171–173.

Phillips McDougall. 2011. The cost and time involved in the discovery, development and authorisation of a new plant biotechnology derived trait. Brussels, Belgium: Crop Life International.

Poerschmann, J., A. Gathmann, J. Augustin, U. Langer, and T. Go´ recki. 2005. Molecular composition of leaves and stems of genetically modified *Bt* and near-isogenic non-*Bt* maize: Characterization of lignin patterns. *Journal of Environmental Quality* 34:1508–1518.

Rebetzke, G.J., A.G. Condon, R.A. Richards, and G.D. Farquhar. Selection for reduced carbon isotope discrimination increases aerial biomass and grain yield of rainfed bread wheat. *Crop Science* 42: 739–745.

Reeves, W.R. et al. 2010. Petition for the determination of non-regulated status for MON 87460. St. Louis, MO: Monsanto.

Reif J.C., P. Zhang, S. Dreisigacker, M.L. Warburton, M. van Ginkel, D. Hoisington, M. Bohn, and A. E. Melchinger. 2005. Wheat genetic diversity trends during domestication and breeding. *Theoretical and Applied Genetics* 110: 859–864.

Richards, R.A. 2006. Physiological traits used in the breeding of new cultivars for water-scarce environments. *Agricultural Water Management* 80(1–3):197–211.

Rijsberman, F.R. 2006. Water scarcity: Fact or fiction? *Agricultural Water Management* 80 (1-3):5–22.

Saibo, N.J.M., T. Lourenco, and M.M. Oliveira. Transcription factors and regulation of photosynthetic and related metabolism under environmental stresses. *Annals of Botany* 103:609–623.

Shewry, P.R., and H.D. Jones. 2005. Transgenic wheat: where do we stand after the first 12 years? *Annals of Applied Biology* 147:1–14.

Singh, B.R., and D.P. Singh. 1995. Agronomic and physiological responses of sorghum, maize, and pearl millet to irrigation. *Field Crops Research* 42:57–67.

Sophocleous, M. 2010. Review: Groundwater management practices, challenges, and innovations in the High Plains aquifer, USA: Lessons and recommended actions. *Hydrogeology Journal* 18:559–575.

Steinemann, A. 2003. Drought indicators and triggers: A stochastic approach to evaluation. *Journal of the American Water Resources Association* 39(5):1217–1233.

Syngenta. 2011. Online at *http://www.syngenta.com/country/us/en/Seeds/Traits/CornTraits/Pages/AgrisureArtesian.aspx*.

Tanksley, S.D., and J.C. Nelson. 1996. Advanced backcross QTL analysis: a method for the simultaneous discovery and transfer of valuable QTLs from unadapted germplasm into elite breeding lines. *Theoretical and Applied Genetics* 92(2):191–203.

Tollefson, J. 2011. Drought-tolerant maize gets U.S. debut. *Nature* 169:144.

Trethowan, R.M., and A. Mujeeb-Kazi. 2008. Novel germplasm resources for improving environmental stress tolerance of hexaploid wheat. *Crop Science* 48:1255–1265.

Tuberosa, R., and S. Salvi. 2006. Genomics-based approaches to improve drought tolerance of crops. *Trends in Plant Science* 11(8):405–412.

Umezawa1, T.M., Y. Fujita, K. Fujita, K. Yamaguchi-Shinozaki, and K. Shinozaki. 2006. Engineering drought tolerance in plants: discovering and tailoring genes to unlock the future. *Current Opinion in Biotechnology* 17:113–122.

University of Illinois, Department of Crop Sciences. 2010. Corn hybrid test results in Illinois, 2010. Urbana-Champaign, IL. Online at *http://vt.cropsci.illinois.edu/corn10/Corn%20Booklet%202010.pdf*.

U.S. Department of Agriculture (USDA), National Agricultural Statistics Service. 2011a. U.S. corn yield. Online at *http://www.nass.usda.gov/Charts_and_Maps/Field_Crops/cornyld.asp.*

U.S. Department of Agriculture (USDA), National Agricultural Statistics Service. 2011b. Prices received: Corn by year, U.S. Washington, DC. Online at *http://www.nass.usda.gov/Charts_and_Maps/Agricultural_Prices/pricecn.asp.*

U.S. Department of Agriculture (USDA), Federal Crop Insurance Corp. 2011c. Pilot biotechnology endorsement. Online at *http://www.rma.usda.gov/policies/2011/11-be.pdf*.

U.S. Department of Agriculture (USDA), Animal and Plant Health Inspection Service. 2011d. Monsanto Company petition (07-CR-191U) for determination of non-regulated status of event MON 87460: Draft environmental assessment. Washington, DC.

Von Korff, M., S. Radovic, W. Choumane, K. Stamati, S.M. Udupa, S. Grando1, S. Ceccarelli, I. Mackay, W. Powell, M. Baum, and M. Morgante. 2009. Asymmetric allele-specific expression in relation to developmental variation and drought stress in barley hybrids. *Plant Journal* 59:14–26.

Wander, M., S. Traina, B. Stinner, and S. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. *Soil Science Society of America Journal* 58:1130–1139.

Wang, Y., M. Beaith, M. Chalifoux, J. Ying, T. Uchacz, C. Sarvas, R. Griffiths, M. Kuzma, J. Wan, and Y. Huang. 2009. Shoot-specific down-regulation of protein farnesyltransferase (a-subunit) for yield protection against drought in canola. *Molecular Plant* 2:191–200.

Wang, Y., Y. Ying, M. Kuzma, M. Califoux, A. Sample, C. McArthur, T. Uchacz, C. Sarvas, J. Wan, D.T. Dennis, P. McCourt, and Y. Huang. 2005. Molecular tailoring of farnesylation for plant drought tolerance and yield protection. *Plant Journal* 43:413–424.

Wilhite, D.A., M.D. Svoboda, and H.J. Hayes. 2007. Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. *Water Resource Management* 21:763–774.

Yang, S., B. Vanderbeld, J. Wan, and Y. Huang. 2010. Narrowing down the targets: Towards successful genetic engineering of drought-tolerant crops. *Molecular Plant* 3(3):469–490.

Yu, T., and B.A. Babcock. 2010. Are U.S. corn and soybean becoming more drought tolerant? *American Journal of Agricultural Econonomics* 92(5):1310–1323.

Yu, W., F. Han, and J.A. Birchler. 2007. Engineered minichromosomes in plants. *Current Opinion in Biotechnology* 18:425–431.

Zeller, S.L., O. Kalinina, S. Brunner, B. Keller, and B. Schmid. 2010. Transgene x environment interactions in genetically modified wheat. *PLoS One* 5(7):e11405.