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Development, Adoption, and Management of Drought-Tolerant Corn in the United States

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Abstract

Drought, a recurring source of crop yield losses and crop failure, often prompts Federal natural disaster and crop insurance payments to U.S. farmers. Few ways exist to substantially reduce yield losses due to drought, although a new tool has recently become available. Drought tolerance produced using conventional breeding methods was first commercially introduced in U.S. corn hybrids in 2011. Genetically engineered (GE) drought tolerance was introduced in hybrids in 2012 but did not become broadly available until 2013. However, the vast majority of drought-tolerant (DT) corn planted in 2016 had one or more GE traits (e.g., herbicide tolerance and/or insect resistance). By 2016, 22 percent of total U.S. planted corn acreage was drought tolerant. Adoption is more concentrated in drought-prone regions of the United States, despite the hybrids' limited abilities to protect against extreme-or-worse droughts. Significant DT corn acreage is also located in non-drought-prone regions and the broader Corn Belt. This report documents the development, adoption, and management of DT corn in the United States, emphasizing the roles of recent and frequent exposure to drought; moisture-conservation practices; GE seed traits and pricing; and irrigation.

Keywords: drought, genetically engineered crops, soil moisture conservation, irrigation, corn, corn yields, Agricultural Resource Management Survey

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A report summary from the Economic Research Service *January 2019*

Development, Adoption, and Management of Drought-Tolerant Corn in the United States

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What Is the Issue?

Droughts have been among the most significant causes of crop yield reductions and losses for centuries. Although Federal disaster program and crop insurance payments tend to be higher during droughts, they typically do not fully compensate farmers for drought-related losses.

Most crop farmers have limited options to reduce the damaging effects of drought. Producers with access to ample sources of irrigation water can, at least partially, mitigate certain drought stress. However, many water-intensive crops—including corn—are mostly grown on non-irrigated cropland. Drought tolerance in corn is a characteristic that has been the subject of research for decades, but has only recently been commercialized. Drought-tolerant (DT) corn produced using conventional breeding methods was commercially introduced in 2011. Hybrids genetically engineered (GE) for drought tolerance were introduced in 2012, but were not broadly available until 2013. GE drought tolerance protects corn plants from drought somewhat differently than conventionally bred drought tolerance and generally took more time to commercialize, both of which can influence the timing of adoption. However, the vast majority of DT corn planted in 2016 had one or more GE traits (e.g., herbicide tolerance and/or insect resistance).

To date, little has been reported about the adoption and use of DT corn in the United States. This report fills that void, examining the development, adoption, and management of DT corn in the United States, emphasizing the roles of recent and frequent exposure to drought, and farmers' moisture-conservation practices, choices of GE seed traits, and irrigation.

What Did the Study Find?

Over one-fifth of U.S. corn acreage was planted with DT corn in 2016. DT corn accounted for only 2 percent of U.S. planted corn acreage in 2012. By 2016, this share had grown to 22 percent. The pace of adoption is similar to the adoption of herbicide-tolerant corn in the early 2000s.

DT corn made up roughly 40 percent of corn acreage in some drought-prone States. In 2016, 42 percent of Nebraska corn acres and 39 percent of Kansas corn acres were planted with DT seed. These and other States with a 25-percent or higher adoption rate, such as South Dakota and Texas, experienced at least one severe-or-worse drought between 2011 and 2015. Northern corn-producing States, such as Minnesota, Wisconsin, and Michigan, experienced less-severe droughts during this time period. Adoption rates in 2016 on corn acres in these States were lower, ranging between 14 and 20 percent.

ERS is a primary source of economic research and analysis from the U.S. Department of Agriculture, providing timely information on economic and policy issues related to agriculture, food, the environment, and rural America.

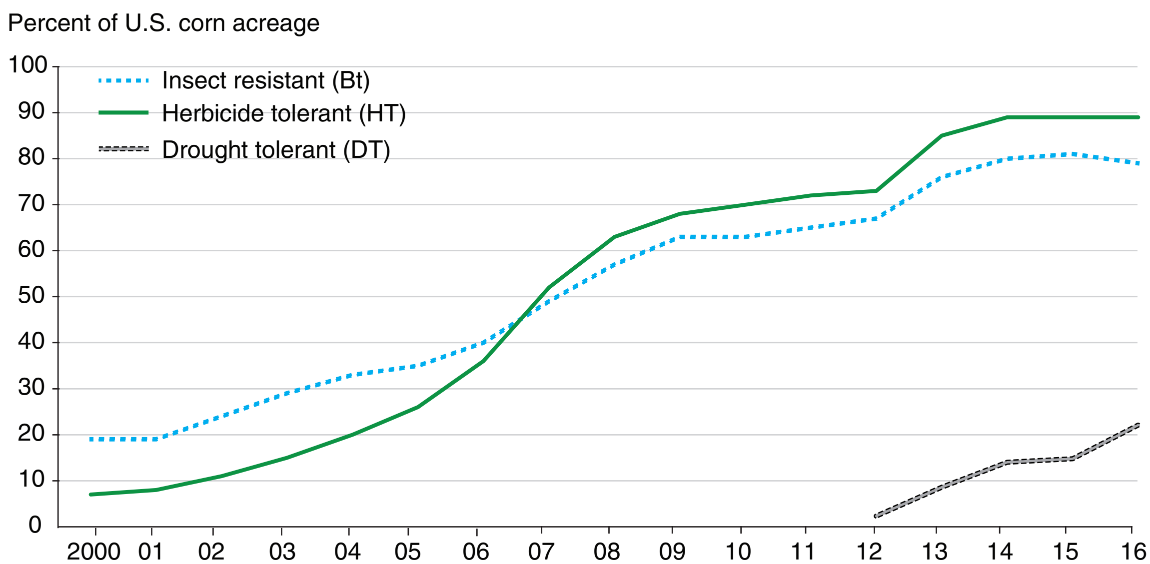
At least 80 percent of DT corn acres were planted in 2016 with seed conventionally bred for drought tolerance. Just under 20 percent of DT corn acres were planted with seed genetically engineered for drought tolerance in 2016. At the national level, 3 percent of all U.S. corn acres in 2016 were planted with seed that had been genetically engineered for drought tolerance.

The vast majority of DT corn in the United States has been genetically engineered for herbicide tolerance, insect resistance, or both. In 2016, 91 percent of DT corn fields were planted with hybrids that were also herbicide tolerant and insect resistant. Herbicide-tolerant (HT) corn can be sprayed with certain weed killers that do not damage the crop. Insect-resistant (Bt) corn is resistant to damage from certain insects that feed on corn.

Some conservation practices are more common on DT corn fields than on non-DT corn fields. Nearly 41 percent of DT corn fields in 2016 were not tilled, compared to 28 percent of non-DT corn fields. More broadly, 62 percent of DT corn fields in 2016 used tillage methods that minimally disturb soils (i.e., conservation tillage), compared to 53 percent of non-DT fields. In 2016, DT corn was more common on fields that had been planted with soybeans in 2015 than fields that had been planted with spring wheat. These trends may reflect climatic influences, since no-till practices and crop rotations influence soil moisture retention. However, the fraction of corn fields that were cover cropped (i.e., planted with a non-corn crop the previous fall to cover the soils over winter) did not vary by DT seed use in 2016.

Figure 2

Percent of U.S. corn acres planted with insect-resistant, herbicide-tolerant, and drought-tolerant hybrids, 2000-16



Note: The insect-resistant (Bt) and herbicide-tolerant (HT) lines also include acreage planted with stacked corn hybrids. Stacked hybrids contain both herbicide tolerance and insect resistance.
Source: USDA, Economic Research Service (ERS), "Adoption of Genetically Engineered Crops in the U.S." data product; USDA, ERS and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey; other sources (see Note to appendix fig. A-1).

How Was the Study Conducted?

We analyze data from the Agricultural Resource Management Survey (ARMS), which is jointly administered by USDA's Economic Research Service and National Agricultural Statistics Service. The report draws on field-level data from the 2016 ARMS survey of corn producers, representing 88 percent of U.S. planted acres in that year. ARMS data on yields, field characteristics, seed choices, tillage, crop rotation, irrigation, and other production practices are linked with county drought data from the U.S. Drought Monitor. We also discuss trends in private firms' DT corn market shares using company-reported data.

Development, Adoption, and Management of Drought-Tolerant Corn in the United States

Introduction

Drought is a recurring cause of widespread yield reduction and, in some cases, crop failure in U.S. agriculture. Using cause-of-loss data from USDA's Risk Management Agency and disaster assistance data from Commodity Credit Corporation expenditure reports, Wallander et al. (2017) find that drought is a major reason for Federal crop insurance indemnity payments and natural disaster payments. In 2012, more than 2,200 counties in 39 States—roughly two-thirds of the United States—were designated as drought disaster areas by USDA (USDA, FSA, 2013). This drought contributed to reductions in the real growth rate of the U.S. economy by between 0.2 and 0.4 percentage points during the last half of 2012 (Kerr, 2012). Corn, a major high-value field crop in the United States, accounted for a significant share of these agricultural losses. In 2012, the national average corn yield was 123.1 bushels per acre, 20 percent lower than the average for the previous 5 years (153.6 bushels per acre over 2007-11) and 27 percent lower than the average for the subsequent 5 years (169.7 bushels per acre over 2013-17) (USDA, NASS, 2018).

How can U.S. farmers, particularly those growing water-intensive crops like corn, decrease the potential for drought-related damage to their crops? Farmers have certain options, though they are limited. They can adjust crop rotations to include less water-intensive crops (e.g., wheat), increase the use of moisture-conserving practices (e.g., conservation tillage), adopt more-efficient irrigation equipment, increase irrigation applications, or add supplemental irrigation (Wallander et al., 2017). These strategies can be used in conjunction with—or possibly in place of—recently commercialized drought-tolerant (DT) corn hybrids. These hybrids can reduce yield losses under mild-to-moderate droughts, but they have limited ability to protect against severe-or-worse droughts (Lybbert and Bell, 2010; Lybbert and Carter, 2015).

Scientists have conducted research on drought tolerance in corn since at least the 1950s (Cooper et al., 2014). Over these decades, some advances in drought tolerance came about indirectly through breeding efforts focused on increasing yields in non-drought conditions (Campos et al., 2006; Yu and Babcock, 2010). However, corn hybrids marketed specifically as drought tolerant were not widely commercially available until 2011.[1] Despite its recent introduction, DT corn acreage made up 22 percent of total U.S. planted corn acreage by 2016. Adoption rates are generally higher in

[1] For decades, plant scientists have used conventional methods to breed corn plants that have become increasingly resistant to drought stress (see Appendix, "Development and Commercialization of DT Corn Hybrids Available in 2016"). Hybrids that performed relatively well under drought conditions were described as being "drought tolerant." Drought tolerance is more accurately described as a characteristic along a continuum rather than a discrete trait. For purposes of this report, however, DT corn refers to hybrids specifically advertised and sold in the United States as "drought tolerant," following large investments in drought-tolerance research, for conventionally bred and genetically engineered seeds, since the 2000s.

western Corn Belt States (e.g., Nebraska and Kansas) than in eastern Corn Belt States (e.g., Indiana and Ohio). Nebraska and Kansas have the highest adoption rates—roughly 42 and 39 percent of their 2016 corn acreage, respectively, was drought tolerant—and adoption in other Corn Belt States has also been considerable (e.g., 16-21 percent of Iowa, Illinois, and Indiana corn acreage).

In this report, we discuss trends in the adoption of DT corn, as well as the research and development underlying currently commercialized DT hybrids. We examine differences in characteristics between DT and non-DT corn fields. We focus on interactions between farmers' seed choices and other crop production and management practices that complement moisture conservation from drought tolerance. We also identify factors that are likely to influence farmers' decisions to plant DT seeds, including the severity and frequency of recent droughts, seed pricing, irrigation, soils, and other field characteristics.

We find that a number of crop production and risk-management practices tend to be jointly adopted with DT corn. Such practices include the use of corn seeds "stacked" with multiple genetically engineered (GE) traits, certain crop rotations, conservation tillage, Federal crop insurance, and irrigation in some areas. However, we do not formally examine the degree to which DT corn use and these other practices are complementary.

Two inputs can be thought of as complementary if greater use of one input tends to make the other input more productive. For example, drought tolerance and insecticide use could be complementary. The moisture-retaining benefits of drought tolerance might be larger on corn crops with more effective insect control because their roots or leaves have not been eaten by insects. In other words, drought tolerance might be compromised in corn crops with insect damage. On the other hand, one might expect some farmers to substitute DT seed use for irrigation under mild drought conditions (Graff et al., 2013). Since drought tolerance and irrigation are performing similar tasks (i.e., providing water to the corn crop when needed), applying a little more irrigation water may not increase the effectiveness of drought tolerance. In other words, some farmers could get the same outcome under mild drought conditions by irrigating non-DT corn or not irrigating DT corn.

How Is Drought Defined and Measured?

Drought is a period of prolonged water shortage that damages crop growth and development. Droughts most commonly result from a combination of below-average precipitation and above-average temperatures. Droughts can be as short as 1 week or can persist across multiple years.

Droughts differ with respect to timing, duration, severity, and geographic area. Drought indices aggregate many factors into a single number that reflects the severity of a drought in a particular area and time. This report uses the U.S. Drought Monitor, a collaboration among USDA, the National Oceanic and Atmospheric Administration, and the National Drought Mitigation Center at the University of Nebraska-Lincoln. It is a widely cited and publicly available index that produces intuitive estimates of the severity and geography of drought.[2]

[2] USDA uses the U.S. Drought Monitor as a guide to making disaster declarations and to help determine eligibility for certain types of loans. The index is also used by USDA's Farm Service Agency to help determine eligibility for the Livestock Forage Program. This program compensates eligible livestock producers for certain grazing losses, including losses resulting from qualifying drought conditions.

The U.S. Drought Monitor sorts drought into five categories based on their severity. The first category, D0 (abnormally dry), is a drought precursor rather than an indicator of an actual drought. This report's primary focus is on droughts that are moderate (D1), severe (D2), extreme (D3), and exceptional (D4).[3] The Drought Monitor categories can be better understood based on their potential impacts: D0, short-term dryness that can slow planting or growth of crops; D1, some damage to crops; D2, crop losses likely; D3, major crop losses; and D4, exceptional and widespread crop losses (U.S. Drought Monitor, 2017). However, actual impacts on farmers' fields will vary with their production and risk-management strategies.

Data Sources

The 2016 Agricultural Resource Management Survey (ARMS) is the main source of data for this report. ARMS is administered jointly by USDA's Economic Research Service (ERS) and National Agricultural Statistics Service (NASS) and is an annual survey of farms' production practices (i.e., chemical use, crop rotations, tillage, and seed choices), farm financial characteristics, and farm household demographics (see box, "Overview of the Agricultural Resource Management Survey"). We use data from Phase II of the 2016 ARMS, a field-level survey of corn producers across 19 States. The 2016 survey is the first that elicited information about farmers' use of drought-tolerant corn seeds; 2016 is also the most recent year for which field-level corn data are available. Our sample represents approximately 88 percent (85.2 million acres) of U.S. planted corn acreage. We supplement the ARMS data with adoption information from seed companies and drought data from the U.S. Drought Monitor.

[3] The U.S. Drought Monitor uses data on temperature, precipitation, soil moisture, hydrology, and fire risk, as well as satellite imagery. Assessments are made, subject to expert review and revision, of the percent area of each county in one or more drought categories (U.S. Drought Monitor, 2017).

Overview of the Agricultural Resource Management Survey (ARMS)

The Agricultural Resource Management Survey (ARMS) is the main source of data used in this report. An annual survey of U.S. farms, ARMS is USDA's primary source of information about the financial conditions, production practices, and economic well-being of the agricultural sector. It is jointly administered by USDA's Economic Research Service and National Agricultural Statistics Service.

ARMS is a multiframe, stratified, and probability-weighted survey conducted in three phases:

- Phase I is undertaken in the summer of the reference year and screens farms for survey eligibility.
- Phase II takes place during the fall of the reference year and collects *field-level* information on production practices, natural resource use, pesticide and fertilizer applications, and other input use for a target crop.
- Phase III is conducted in the spring after the reference year and collects *farm-level* information about finances, operator and household characteristics, and demographics. Farms surveyed for a target crop in Phase II are also asked to complete the Phase III survey and form a subset of the Phase III sample. However, Phase III samples farms of all types (e.g., row crops, livestock, specialty crops) and all sizes (e.g., very small to very large) across the contiguous 48 States.

Data for this report are primarily from Phase II of the 2016 ARMS. ARMS surveys the same target crop every 4 to 6 years. The two most recent corn surveys were 2010 and 2016. Many major field crops (e.g., corn, soybeans, wheat, cotton, rice) are surveyed on a similarly rotating schedule, though not all major field crops are surveyed. Each of the surveyed fields (one per farm in the sample) is randomly selected. Enumerators conduct the survey in person, which contributes to data accuracy and fewer missing responses.

The 2016 Phase II survey provided roughly 2,100 usable responses. The trends depicted and discussed in this report rely on subsets of these responses. This report accounts for the statistically complex survey design to ensure that findings are statistically representative of U.S. corn fields and acreage.

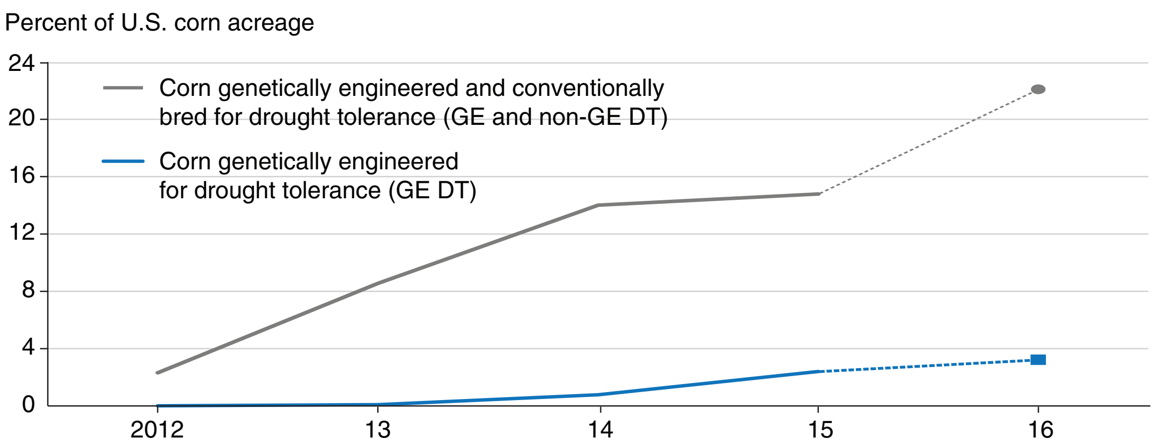
Development and Adoption of DT Corn

Based on USDA, ARMS data, over one-fifth (22 percent, or 18.6 million acres) of U.S. corn acres were planted with drought-tolerant (DT) corn in 2016. This is a substantial increase over the 2 percent of corn acreage estimated to have been planted with DT corn in 2012 based on industry data for DuPont Pioneer, Monsanto, and Syngenta corn hybrids. Much of the increase in adoption was for DT corn with conventionally bred drought tolerance (non-GE), which was commercially introduced in 2011. Hybrids genetically engineered (GE) for drought tolerance were released on a limited basis in 2012 and became more broadly available in 2013. Regardless of whether the drought-tolerance characteristic was GE or non-GE, the bulk of DT corn planted in 2016 had one or more GE traits (e.g., herbicide tolerance and/or insect resistance).

The diffusion of GE DT corn has lagged behind the diffusion of the non-GE DT hybrids (fig. 1).[4] Roughly 250 farmers planted up to 40 acres each of the GE hybrids during the initial 2012 release. This resulted in 10,000 acres of GE DT corn. Over 2,000 farmers planted GE DT corn the following year (Waltz, 2014). By 2016, GE DT hybrids accounted for 3 percent of total U.S. corn acreage, though they remained a small share of total DT acreage.[5]

Figure 1

Diffusion of drought-tolerant (DT) corn during first 5 years of commercialization



Note: GE DT corn was introduced in 2012, while non-GE DT corn was commercialized in 2011. For 2012-15, DT corn acreage is taken from various sources (see "Source" to appendix fig. A-1) and then divided by total planted acreage of corn for grain. For 2016, the total DT adoption rate is calculated from Phase II ARMS data; the 2016 DT GE adoption rate is taken from various sources (see "Source" to appendix fig. A-1) and then divided by total planted acreage of corn for grain. The dotted line segment between 2015 and 2016 underscores the differences in sources between the years 2012-15 and 2016.

Source: USDA, National Agricultural Statistics Service (2017) and various other sources (see "Source" to appendix fig. A-1); USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey (ARMS).

[4] For purposes of this report, "GE DT" corn refers to hybrids with genetically engineered drought tolerance, while "non-GE DT" corn refers to hybrids with conventionally bred drought tolerance. As noted throughout the report, the vast majority of 2016 DT corn fields were planted to hybrids with at least one GE trait.

[5] This could be the result of potential differences between the set of GE varieties and non-GE varieties offered to farmers in certain areas, as well as potential differences in seed pricing. Lower adoption of GE DT corn could also result from some farmers' concerns about GE-related "yield drag" (Edmeades, 2013). In the early years of genetic engineering, relatively few GE corn hybrids were available, including some lower yielding varieties. This "yield drag" dissipated as GE traits were introduced to many more corn varieties (Fernandez-Cornejo and Caswell, 2006).

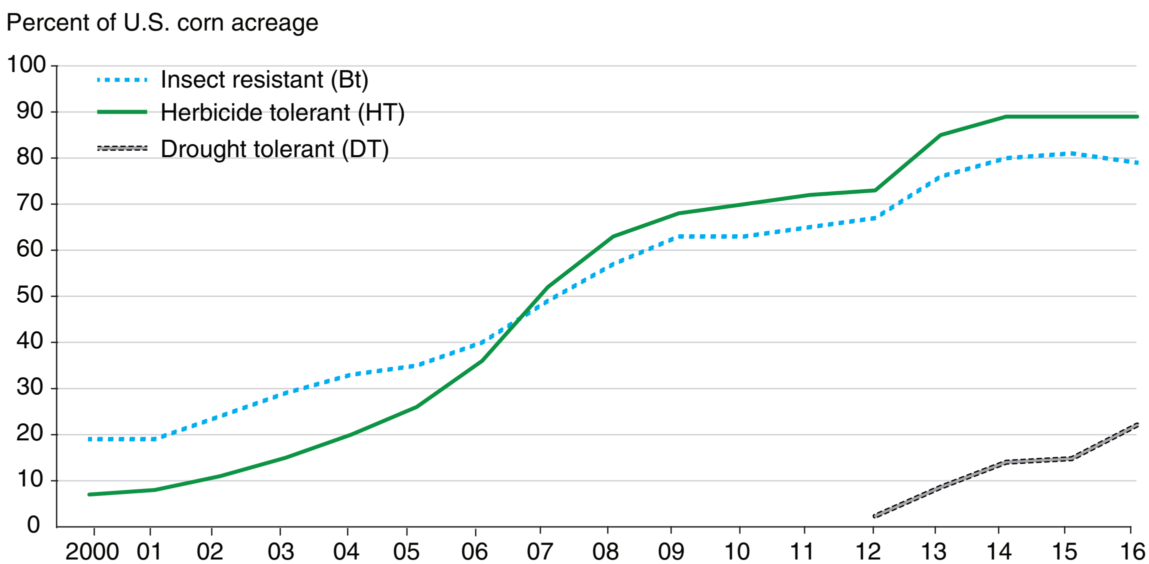
The differences in commercialization times and adoption of GE and non-GE DT corn are partly a reflection of differences in the research and development (R&D) underlying these seeds (see the next subsection and Appendix, “Development and Commercialization of DT Corn Hybrids Available in 2016”). The R&D underlying both GE and non-GE DT corn took place on somewhat similar timescales (Edmeades, 2013). However, seed companies that currently sell non-GE DT seeds are continuing to research methods of genetically engineering drought tolerance (Habben et al., 2014). Commercialization of these hybrids, with implications for DT corn seed prices, could contribute to greater uptake of GE DT corn and increase the GE share of the overall DT market.

These early trends in DT corn adoption can be better understood within the broader context and longer history of GE corn adoption. Two types of GE traits in corn have been widely adopted by U.S. farmers since their commercial introduction in 1996: herbicide tolerance (HT) and insect resistance (Bt). As of 2016, farmers can plant corn seed that is DT, HT, Bt, or some combination of these three. Adoption of DT corn is currently much less common than adoption of HT corn or Bt corn. However, the pace of DT corn acreage expansion is similar to the early years of HT corn adoption and faster than the pace of early Bt corn adoption (fig. 2).

Generally, HT and Bt traits benefit producers by reducing the damage caused by pests. Additional benefits from HT or Bt traits include reduced insecticide use, lower fuel and equipment costs, time and labor savings, and lower pest-induced yield losses (Fernandez-Cornejo et al., 2014; Wechsler et al., 2018; Wechsler and Smith, 2018).

Figure 2

Percent of U.S. corn acres planted with insect-resistant, herbicide-tolerant, and drought-tolerant hybrids, 2000-16



Note: The insect-resistant (Bt) and herbicide-tolerant (HT) lines also include acreage planted with stacked corn hybrids. Stacked hybrids contain both herbicide tolerance and insect resistance.
Source: USDA, Economic Research Service (ERS), "Adoption of Genetically Engineered Crops in the U.S." data product; USDA, ERS and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey; other sources (see Note to appendix fig. A-1).

HT crops are immune to specific herbicides designed to kill various weeds, often both broad-leafs and grasses. This enables farmers to spray HT crops at any point during the growing season, especially after crop emergence. By contrast, non-HT corn hybrids are severely damaged by many herbicides. As of 2016, approximately 9 out of every 10 U.S. corn acres were planted with HT seeds (fig. 2).[6]

The Bt trait protects the corn crop from certain damaging insect pests. These hybrids have been genetically engineered—through insertion of genes from a soil bacterium (*Bacillus thuringiensis*)—to produce an insecticidal protein that is toxic to particular insects. In 2016, nearly 8 out of every 10 U.S. corn acres were planted with Bt seeds (fig. 2).

Research Underlying the Development of Drought Tolerance in Corn

Corn is among the set of major field crops that are sensitive to drought. Other major crops, including rice, potatoes, and several vegetables, are more sensitive to drought than corn, but they are also more likely to be grown on irrigated land (Brouwer et al., 1989). Because of these drought sensitivities, plant scientists have spent decades identifying traits for increasing major crop yields in water-limited growing conditions (Ludlow and Muchow, 1990).

Research to develop drought tolerance in corn began in the United States in the 1950s. On research plots in southeastern Nebraska, plant breeders used side-by-side trials with drought and irrigation treatments to select hybrids directly for yield performance under drought conditions (Cooper et al., 2014). The impacts of water-limited growing conditions on corn yields continued to be studied in the 1960s (Claassen and Shaw, 1970), and by the 1970s, international breeding programs had been established to select corn open-pollinated varieties and hybrids for improved drought tolerance (Edmeades et al., 1999). Although modern corn hybrids have become more resilient to various stresses because of traditional breeding programs, several drought-tolerant hybrids have been developed through targeted research aided by advanced experimental designs, crop and computational models, and genetic engineering (Bruce et al., 2002).[7]

The public and private sectors have intensively researched stress tolerance in field crops over the past several decades. To date, far more research has been conducted on tolerance to biotic stresses (e.g., plant pests and diseases) than on tolerance to abiotic stresses (e.g., droughts, heat, and freezes), mainly because developing field crops with environmental stress tolerance has been more difficult (Heisey and Day Rubenstein, 2015). Development of DT corn has faced two significant challenges. First, corn undergoes a set of complex physiological responses to drought that vary with a drought's timing, duration, and severity. These responses are not governed by a single gene. Consequently, modifying or otherwise altering one gene—or even a small number of genes—may not confer drought tolerance. Second, the effects of drought stress on the corn plant are not necessarily the same as heat stress effects (Edmeades, 2013; Heisey and Day Rubenstein, 2015). Isolating responses to high temperatures separately from responses to moisture stress has been difficult.

[6] Many GE corn hybrids are "stacked" with both HT and Bt traits. By 2017, stacked hybrids accounted for over 77 percent of total U.S. planted acres, with corn acreage dedicated to a single trait (e.g., HT or Bt) generally declining since 2005-07.

[7] Using Illinois and Indiana data between 1980 and 2008, Yu and Babcock (2010) find that corn yield losses due to moderate droughts decreased by 15 bushels over the 29-year period. However, the period 1980-2008 predates commercialization of DT corn. The authors hypothesize this increased tolerance could arise from the widespread adoption of GE traits or better management resulting from shifts of corn production to larger farms.

Seed companies have responded to the challenges associated with developing DT hybrids with different approaches (see box, "How Do Drought-Tolerant Corn Hybrids Work?"). Broadly, all DT hybrids counteract the plant's natural tendency to divert energy from reproductive growth (e.g., production of many kernels) toward plant survival under severe moisture stress (Waltz, 2014). However, drought-tolerance research is still in a relatively early stage, and other methods of inducing resilience to moisture stress in corn and other crops continue to be identified.[8]

How Do Drought-Tolerant Corn Hybrids Work?

Drought-tolerant (DT) corn is resilient to drought stress because of improvements in at least one of three factors: (1) total water taken up by the plant, (2) the conversion efficiency of water to biomass (water use efficiency), and (3) the fraction of biomass that becomes grain (the harvest index).[9] Increases in root depth and good weed control improve water uptake.[10] Several mechanisms influence water use efficiency, though maintenance of healthy leaves with adequate nutrients (i.e., improvements in a corn plant's ability to "stay green") is particularly important. The number of kernels per ear that eventually form influences the harvest index and is tied directly to yields (Edmeades, 2013). The relative importance of these three factors for determining yields under drought varies across the growing season.[11] Genetic engineering (GE) can change their relative influence and function.

Drought Tolerance Produced with Genetic Engineering (GE DT)

The GE DT corn available in 2016 relies on a gene from the soil bacterium *Bacillus subtilis,* which has been inserted into the corn plant's genetic material. This gene causes the plant to express a certain type of protein: cold shock protein B (CSPB). Bacterial CSPs help regulate adaptation to cold stress following rapid decreases in temperature, but they also regulate other biological functions under normal conditions (Horn et al., 2007). In GE DT corn, this protein binds to certain molecules and helps to "unfold" some molecular structures that typically "fold" in response to drought. This helps lessen the effects of drought on photosynthesis, carbon dioxide passage through leaf pores, and the plant's conversion of inorganic carbon to organic compounds (Castiglioni et al., 2008; Waltz, 2014).

—continued

[8] For example, DuPont Pioneer has developed and tested corn hybrids that have been genetically engineered to suppress enzymes that help the plant produce ethylene gas. Ethylene is a hormone that regulates different aspects of growth and development of the plant during certain environmental stresses, including drought (Habben et al., 2014).

[9] These three factors determine corn yields. That is, yields are equal to the product of water uptake, water use efficiency, and the harvest index (Passioura, 1977; Edmeades, 2013).

[10] DT hybrids may have differences in root systems that contribute to reduced yield losses under drought (Hammer et al., 2009; Chang et al., 2014).

[11] Yields are likely to decline if the plant is exposed to drought conditions in two critical growth phases, flowering and grain fill (Campos et al., 2006; Edmeades, 2013; Nemali et al., 2015). The flowering stage includes the period in which pollen begins to shed and silks emerge. The grain-fill stage begins with pollination and kernel development and ends when the kernels are mature.

How Do Drought-Tolerant Corn Hybrids Work?—continued

The mechanisms through which expression of CSPB confers drought tolerance in the field continue to be explored. Early field trial evidence for these hybrids grown under water-limited conditions immediately prior to pollen shed show they increased leaf growth, chlorophyll content, and photosynthesis rates relative to non-DT controls. These hybrids also showed improvements in the number of plants with kernel-bearing ears and number of kernels per plant (Castiglioni et al., 2008). More recent research points to the role of reduced leaf growth during silking, which slows water taken up by the plant and thus increases water use efficiency. With these simultaneous reductions in stress, the plant devotes more energy to ear growth. These larger ears had increased kernel development, leading to higher corn yields under water-limited conditions than non-DT controls (Nemali et al., 2015).

Drought Tolerance Produced Without Genetic Engineering (Non-GE DT)

Molecular breeding programs that identify sets of genes governing or associated with drought tolerance have resulted in the development of conventionally bred DT corn. There have been two broad approaches to developing the non-GE DT corn hybrids available as of 2016. In the first approach, known as "Mapping As You Go," the genetic material of the plants used for breeding is mapped as new generations of plants are bred. Since the relationships between a plant's genes and the desired physical trait (e.g., drought tolerance) can change over time, frequent mapping ensures the relationships remain relevant for breeding (Podlich et al., 2004). The second approach begins with genetic analysis, rather than starting from hybrids that are already commercially successful. Rare or minor forms of gene variants associated with drought tolerance are identified, then plant breeders are instructed to select hybrids based on the results of this identification process (Kishore et al., 2014).

Field trial evidence shows that several non-GE corn hybrids have differences in water use efficiency rather than total water taken up by the plant. A greater percentage of water during the flowering growth stage (when pollen sheds and silks emerge) is used to support kernel growth (Cooper et al., 2014; Gaffney et al., 2015). Simulations suggest this conservation of early-season water could result from reductions in evaporation of water through the plants' leaves (e.g., transpiration) during periods of higher vapor pressure deficit.[12] Transpiration efficiency (e.g., biomass produced per unit of water lost) increases and helps to redirect water use from growth stages to reproductive stages of development (Messina et al., 2015).

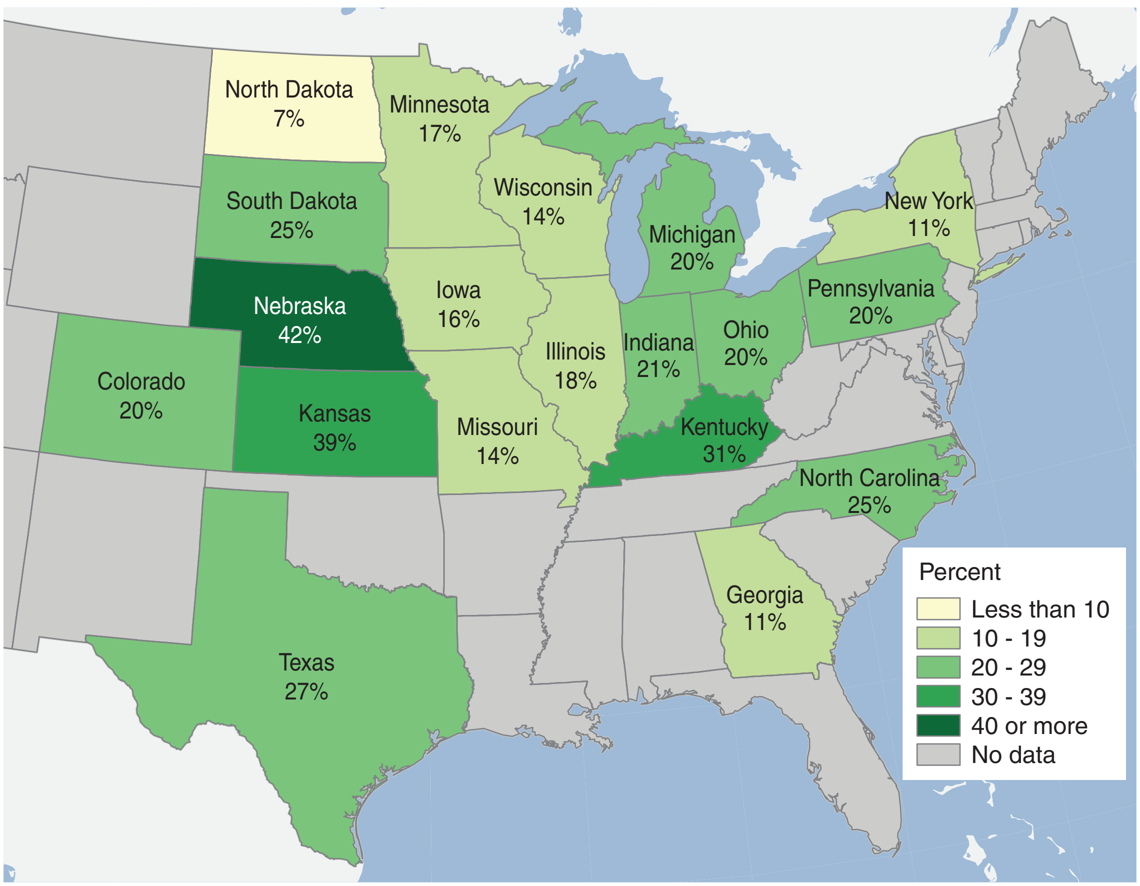
[12] Vapor pressure deficit (VPD) is the difference between water in the air at any given point in time and how much water the air can hold when saturated. Because corn plants respond to higher VPD by increasing transpiration, higher VPD can result in lack of moisture available for the plant.

Geography of DT Corn Adoption and Drought Exposure

In 2016, drought-tolerant (DT) corn was grown in 18 States where at least 1 million acres of corn were planted (fig. 3). However, adoption rates were highest in areas where DT corn was developed and initially marketed. Over 4 million acres of DT corn—or 42 percent of State corn acreage—were planted in Nebraska, a semi-arid western Corn Belt State. Approximately 2 million acres of DT corn (39 percent of State corn acreage) were cultivated in Kansas, a State with a relatively similar climate. Corn Belt States with relatively wetter climates—Iowa, Illinois, and Indiana—had 1.1 to 2.2 million DT corn acres each, though these acreages represent smaller shares of each State's total, roughly 16 to 21 percent. In the northern Corn Belt, Minnesota and South Dakota each had 1.4 million DT acres, representing 17 and 25 percent of these State's respective corn acreage. Adoption has also been significant in the eastern Corn Belt States near the Great Lakes (e.g., Ohio, Wisconsin, and Michigan).

Figure 3

Percent of each State's corn acreage planted with drought-tolerant (DT) hybrids, 2016

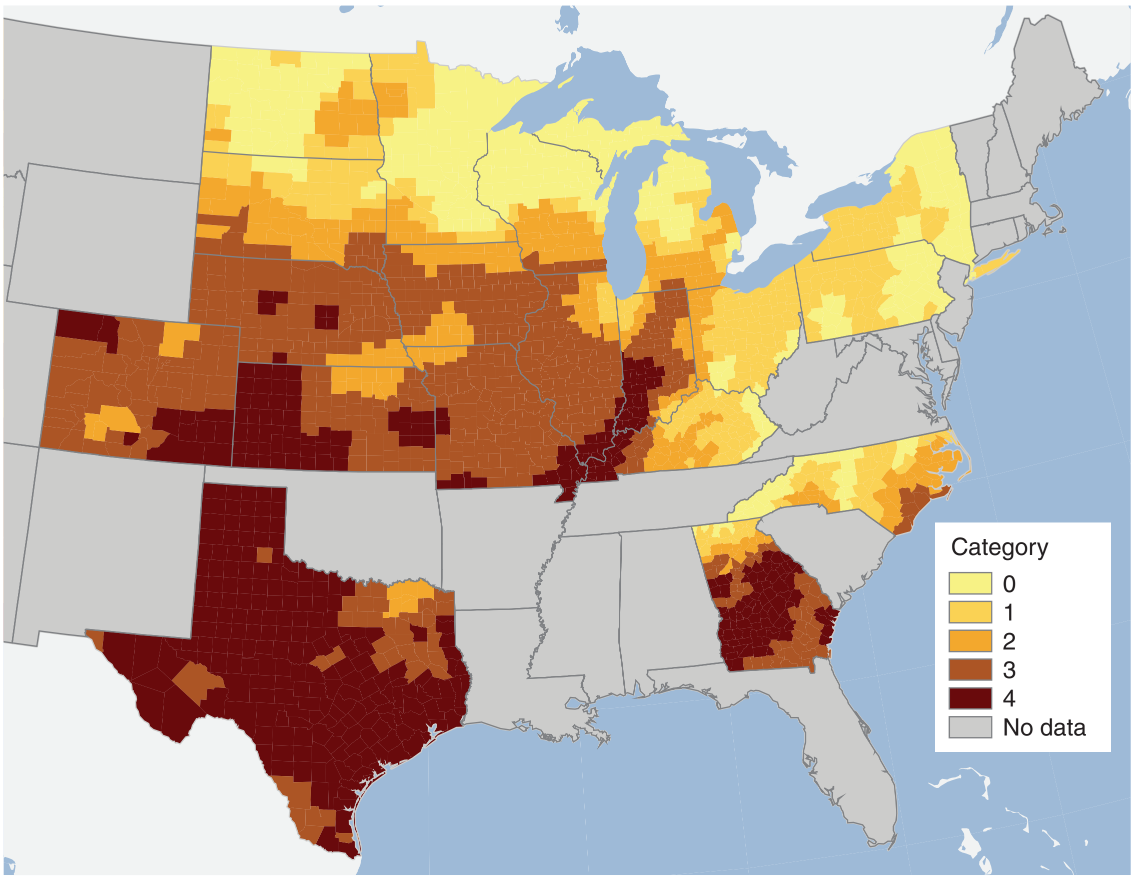


Note: In 2016, U.S. DT corn acreage planted totaled 18.6 million acres.
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Between 2011 and 2015, the most damaging droughts experienced during the corn-growing season in each county of our 19-State survey area tended to be classified as severe, extreme, or exceptional (fig. 4). The most severe drought for many counties during this period occurred in 2012 and was particularly serious in Colorado, western Texas and Kansas, southern Missouri and Illinois, western Kentucky, and certain areas of Indiana and Georgia. Many of the counties affected by the 2012 drought in the western Corn Belt also experienced drought in 2011 and 2013.[13] However, many high-latitude counties in Minnesota, Wisconsin, Michigan, Ohio, Pennsylvania, and New York did not experience a severe-or-worse drought from 2011 to 2015.

Figure 4

Most severe drought during corn-growing season between 2011 and 2015, by county



Note: The numeric drought categories are interpreted as: none or abnormally dry (0), moderate drought (1), severe drought (2), extreme drought (3), and exceptional drought (4). The data are for July months between 2011 and 2015. Although U.S. Drought Monitor data are available for all counties in this period, the 2016 Agricultural Resource Management Survey Phase II surveyed producers in 19 States (see fig. 3).
Source: National Drought Mitigation Center at the University of Nebraska-Lincoln, USDA, multiple agencies, and the National Oceanic and Atmospheric Administration, 2011-15 U.S. Drought Monitor.

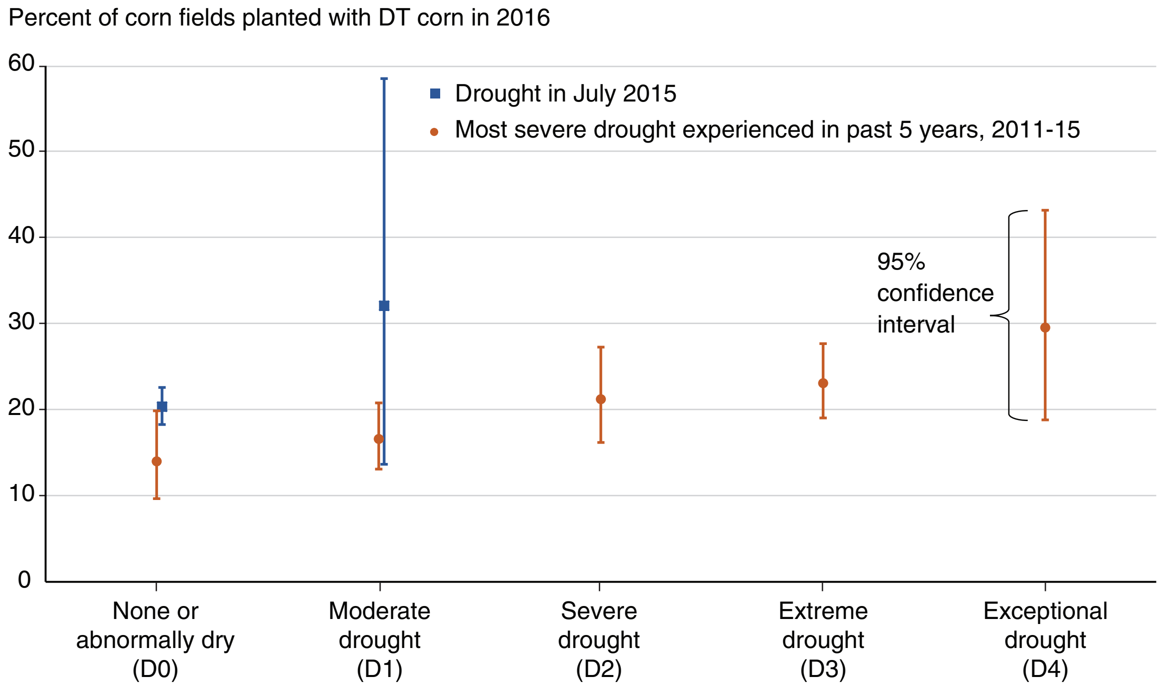
[13] The 2011 drought was especially severe in Texas, Oklahoma, New Mexico, and southwest Kansas (Tadesse et al., 2015). Agricultural losses due to the 2011 drought in Texas alone were $7.6 billion (Guerrero, 2013). Texas is a drought-prone State: 89 percent of Texas counties experienced an extreme-or-worse drought in 2011, while 37 percent of counties experienced an extreme-or-worse drought in 2013 (U.S. Drought Monitor, 2017).

Regional differences in drought severity and recentness of exposure significantly influence adoption of DT corn (fig. 5). Only 14 percent of fields located in areas that did not experience a July drought (i.e., none or abnormally dry classifications) from 2011 to 2015 were planted with DT corn in 2016. By contrast, 30 percent of corn fields located in areas where the most severe July drought was "exceptional" (i.e., D4 classification) at some point between 2011 and 2015 were planted with DT hybrids in 2016.

If recent exposure to drought reflects regional differences in drought risk, then the positive correlation between drought exposure and DT corn adoption likely reflects the fact that farmers facing greater drought risk may experience larger benefits of adoption, at least up to moderate drought conditions (see box, "How Do Drought-Tolerant Corn Hybrids Work?"). In addition, exposure to drought may influence farmers' perceptions about the drought risk they face, so recent events could encourage adoption even in areas with lower risk.

Figure 5

Percent of corn fields planted with drought-tolerant (DT) corn in 2016, by 2015 drought magnitude and maximum drought magnitude between 2011 and 2015

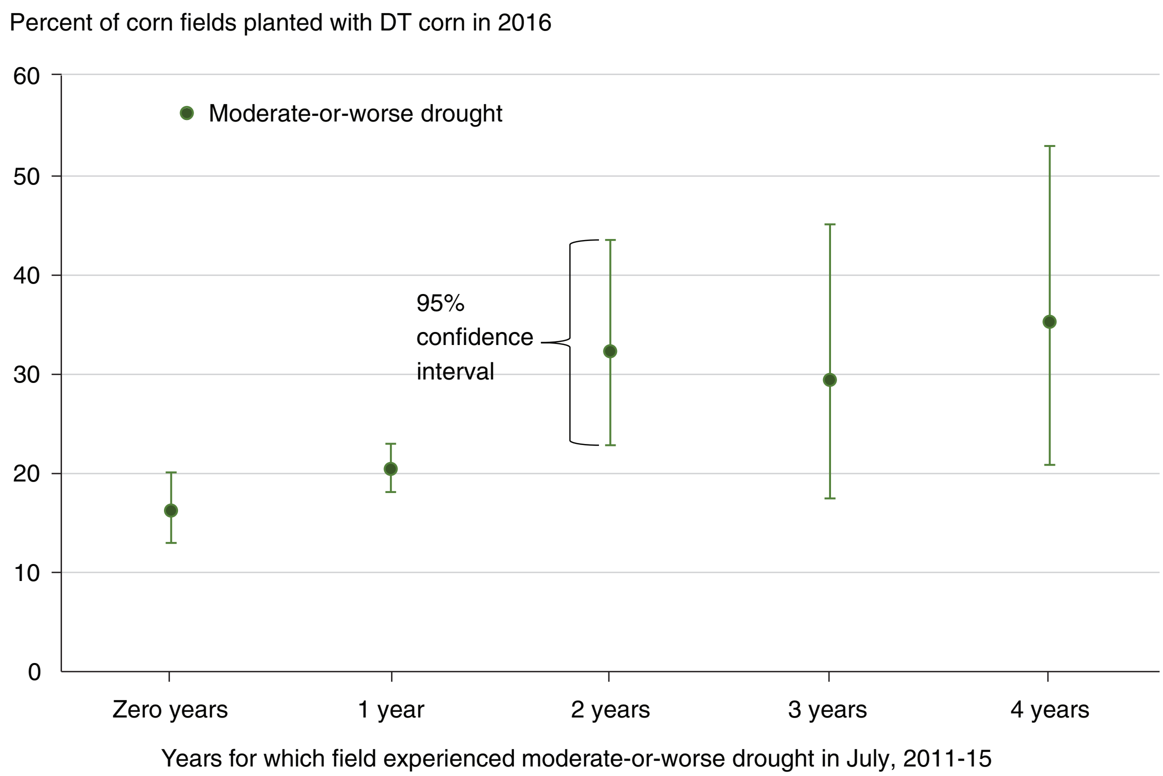


Note: The vertical axis indicates: (1) the percent of 2016 corn fields that were DT for a given drought-magnitude category in July 2015 (blue line) and (2) the percent of 2016 corn fields that were DT based on the maximum July drought-magnitude experienced on the field in the past 5 years (orange line). For example, just under 30 percent of corn fields whose worst July drought in the past 5 years was an exceptional (D4) drought were planted with DT corn in 2016. The vertical bars are logit-transformed 95-percent confidence intervals (CI) to account for the lower (0 percent) and upper (100 percent) limits of percentages. A 95-percent CI has this interpretation: if the set of all 2016 U.S. corn farmers were sampled 1,000 times and interval estimates were made each time, then approximately 950 of these intervals would contain the true but unknown estimate. That is, a 95-percent CI is a range of values likely to contain the true but unknown estimate.
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey; National Drought Mitigation Center at the University of Nebraska-Lincoln, USDA, multiple agencies, and the National Oceanic and Atmospheric Administration, 2011-15 U.S. Drought Monitor.

Drought frequency also significantly influences adoption of DT corn (fig. 6). Roughly 21 percent of fields that had experienced only one moderate-or-worse July drought between 2011 and 2015 were DT in 2016. However, 29-35 percent of fields that had experienced three or four moderate-or-worse July droughts over the prior 5-year period were DT in 2016. This complements the prior analysis and shows that both increased severity and increased frequency are associated with higher rates of adoption, which suggests a link between drought proneness and adoption.[14]

Figure 6

Percent of corn fields planted with drought-tolerant (DT) corn in 2016, by drought frequency between 2011 and 2015



Note: The vertical axis indicates the percent of 2016 corn fields that were DT for a given number of years in which the county had experienced a moderate-or-worse drought in the past 5 years (2011-15). For example, 35 percent of corn fields that had experienced a drought in 4 years during 2011-15 were DT. The vertical bars are logit-transformed 95-percent confidence intervals to account for the lower (0 percent) and upper (100 percent) limits of percentages. See Note to fig. 5 for an explanation about interpretation of 95-percent confidence intervals.
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey; National Drought Mitigation Center at the University of Nebraska-Lincoln, USDA, multiple agencies, and the National Oceanic and Atmospheric Administration, 2011-15 U.S. Drought Monitor.

[14] Our results are qualitatively similar regardless of whether we use the U.S. Drought Monitor or the Palmer Modified Drought Index (Heddinghaus and Sabol, 1991). Adoption is generally increasing in relation to drought severity, recency, and frequency. As with our results using the U.S. Drought Monitor, we are able to say less about adoption in areas with very severe, recent, or frequent droughts because of wide confidence intervals due to relatively fewer observations.

Potential Complementarities Among Drought Tolerance, Herbicide Tolerance, and Insect Resistance

Herbicide-tolerant (HT) and/or insect-resistant (Bt) traits tend to be combined with drought tolerance in corn seeds. Of the GE corn fields with drought-tolerant corn in 2016, 95 percent were planted with hybrids that were also herbicide tolerant, 96 percent were planted with insect-resistant hybrids, and 91 percent were planted with stacked hybrids (which have both herbicide tolerance and insect resistance). Similarly, 92 percent of non-DT GE corn fields were planted with HT and 85 percent were planted with Bt hybrids. Stacked traits on non-DT corn fields were somewhat less common: 77 percent of non-DT corn fields were planted with corn having both HT and Bt traits.

In many areas, DT, HT, or Bt seeds are planted on fields with the potential to earn high corn revenues, either because local corn prices are high and/or because soils are highly productive. For example, HT and Bt corn is planted at high rates in Iowa, Illinois, and other regions of the Corn Belt that can experience both severe drought and pest pressure in certain years (Wechsler et al., 2018). Planting HT or Bt seeds in areas where pest pressure is high could increase the benefits associated with DT seed use, and thus DT adoption rates, in drought-prone regions. Company seed pricing strategies could also encourage joint use of multiple GE traits (see box, "Bundled Pricing and Corn Seed Premiums").

It is likely that herbicide tolerance, insect resistance, and drought tolerance are complementary (e.g., Shi et al., 2010; Yu and Babcock, 2010; Edgerton et al., 2012).[15] In other words, use of one trait is likely to increase the effectiveness of one or both of the other two traits. From an agronomic perspective, potential complementarity could exist because drought damages can be larger in weed- and insect-infested corn fields (Godfrey et al., 1992; Dun et al., 2010). Weeds compete with corn for water, thus decreasing soil moisture and amplifying drought damage (e.g., Berger et al., 2010). Superior weed protection in HT corn fields reduces the chances of a damaging weed infestation. Moreover, prior research has demonstrated that herbicide tolerance facilitates the use of conservation tillage (Fernandez-Cornejo et al., 2012; Perry et al., 2016). Reductions in tillage leave more crop residue on the field and increase soil organic matter, contributing to greater soil moisture retention.

Similarly, Bt traits protect against soil-dwelling insects, like corn rootworm, that feed on plant roots (Wechsler and Smith, 2018). Bt corn is more likely to have well-functioning root systems if effectively protected against such pests, which can contribute to more effective uptake of water in the plant (Comas et al., 2013). Moreover, Bt traits protect against some above-ground pests like the European corn borer that can interfere with the plant's internal water flow (Hutchinson et al., 2010). The moisture absorption benefits from drought tolerance could be lower in crops with damaged roots, lower root mass, and/or compromised internal water flow (e.g., Li et al., 2009).

[15] Shi et al. (2010) find evidence that adopters of corn seeds with protection against corn rootworms (a Bt trait) view herbicide tolerance as complementary.

Bundled Pricing and Corn Seed Premiums

The average price of seed traits tends to be lower when these traits are "bundled." For example, suppose a bag of corn seed without herbicide-tolerance (HT), insect-resistance (Bt), or drought-tolerance traits costs $225. Further, suppose that another bag of corn seed resembles the first bag in all respects, except that it has a single HT trait and costs $250. Similarly, suppose that a third bag of corn seed resembles the first bag in all respects, except that it instead has a single Bt trait and (like the second bag) costs $250. It is unlikely that a farmer purchasing a stacked seed (which contains both the HT and Bt traits) would pay $275 ($225 + $25 + $25) per bag. Farmers purchasing seed with multiple traits tend to get a small discount for each additional trait purchased. These discounts may play a significant role in farmers' seed choice decisions. Using proprietary survey data of farms across 12 corn-growing States during 2000-2007, Shi et al. (2010) find strong statistical evidence of bundled pricing in U.S. corn seed markets.[16]

Shi et al. (2010) also estimate seed premiums (relative to conventional hybrids) of $25-$46 per bag for certain Bt traits and $9.63 for certain HT traits. This is comparable to results in Wechsler and Smith (2018), who estimate mean price premiums per bag for corn rootworm Bt traits of $16.75 (in 2005) and $33.35 (in 2010) using ARMS data. Wechsler et al. (2018) estimated a 28-percent premium for glyphosate-tolerant HT seeds by analyzing ARMS data from years 2005 and 2010, which is slightly larger than the HT premiums (in percentage terms) estimated in Shi et al. (2010).

Using 2016 ARMS data, we estimate the drought-tolerant (DT) corn seed premium to be $10 per bag. This is calculated as mean seed costs per bag on fields planted with corn with DT, HT, and Bt traits ($264.31) minus mean seed costs per bag on fields planted with corn with only HT and Bt traits ($254.26). Seeds with drought tolerance produced using genetic engineering (GE DT) may be higher priced than seeds with drought tolerance produced using conventional breeding (non-GE DT) seeds (Minford, 2015). Since ARMS does not inquire separately about GE and non-GE DT adoption, we are unable to estimate separate premiums for GE and non-GE DT seeds.

The weight that U.S. farmers attach to seed premiums when choosing whether to plant DT corn is unknown, in part because of a lack of detailed pricing data. Relatively more is known about the importance of DT seed premiums among smallholder farmers in Sub-Saharan Africa, where the Drought Tolerant Maize for Africa (DTMA) project released more than 200 varieties of DT corn between 2007 and 2015. In 2013, high DT corn seed prices were found to be a barrier to adoption for farmers in Ethiopia, Tanzania, Uganda, and Malawi (Fisher et al., 2015). In Malawi, where local corn varieties are typically grown, farmers were 78 percent more likely to plant DT corn if the seeds were provided to them for free under the country's Farm Input Subsidy Program (Holden and Fisher, 2015).

Other barriers to DT corn adoption among smallholders in DTMA countries include inadequate information, lack of labor and other resources, and farmers' (potentially uninformed) perceptions of the varieties. These factors have most likely not impacted adoption of DT corn in the United States, where the characteristics of production environments (e.g., farm size, labor availability, modern equipment, credit access) differ vastly from those targeted by DTMA.

[16] Synergies in research and development among multiple GE traits could explain bundled pricing. For example, economies of scope in seed production could result from cost savings due to sharing of scientific knowledge, equipment, or managerial expertise. These joint cost reductions could be passed on to farmers. Bundled pricing may also result from discriminatory pricing (i.e., charging customers different prices based on their underlying differences in willingness-to-pay) and input complementarity (i.e., production environments in which use of one input tends to make the other input more productive) (Shi et al., 2010).

Soil Moisture Conservation and Irrigation

Production practices that conserve soil moisture, such as conservation tillage and crop rotations, have been used for decades in corn production (see box, "Crop Farmers' Strategies to Partially Limit Drought Damages or Increase Resilience to Drought"). In drier States, such as Nebraska and Kansas, for example, adoption of conservation tillage was practiced by some farmers even before the Federal Government began its promotion through voluntary conservation programs (e.g., USDA's Environmental Quality Incentives Program) and recent advances in weed control and seed technologies (Bull and Sandretto, 1996). These practices conserve soil moisture by increasing infiltration of rainfall and reducing moisture lost to the atmosphere (i.e., evaporation of moisture from the soil).

Farmers can reduce moisture loss from their soils using various methods. One option is to increase the amount of residue on the soil surface. When crops are harvested, stalks and straw tend to be left on the field. These residues protect the soil from physical damage caused by heavy rains, which can break down soil aggregates and lead to soil compaction. Crop residues also reduce water runoff by increasing the amount of time rainfall has to soak into the field (Dao, 1992; Unger et al., 1991). Finally, residues shield the soil from the sun and wind, slowing evaporation (Klocke et al., 2009).

Farmers can also increase their soil's ability to retain moisture by increasing soil organic matter, which is formed as surface residues decompose and become incorporated into the soil. Soil organic matter increases water infiltration and soil moisture-holding capacity—the maximum amount of water that the soil can hold (Kansas State University, 2012). When residue decomposes in the soil, it leaves behind pores where water can be stored. Less directly, soil organic matter increases soil moisture by improving soil structure. Compounds released by the microbial decomposition of organic matter help the soil particles form into aggregates. Soil aggregation creates pores, channels, and chambers that increase water infiltration. These improvements in soil structure enable deeper root penetration, increasing crops' access to stored soil moisture.

Crop Farmers' Strategies to Partially Limit Drought Damages or Increase Resilience to Drought

Many strategies are available to farmers to help limit downside risks from drought (Wallander et al., 2017), but few by themselves would be expected to substantially reduce yield losses due to drought. These strategies can be grouped into four categories: (1) technology adoption, (2) use of conservation practices, (3) Government program enrollment, and (4) financial management options (Smit and Skinner, 2002; Malcolm et al., 2012). They differ widely with respect to implementation costs, ease and convenience of use, the timeframes over which they increase resilience, regional availability or feasibility, and the benefits they provide (see table). However, farmers choosing one or more are likely to fare better, on average, under certain stresses (e.g., reductions in yield losses or in revenue loss).

Adoption of new technologies—embedded in seeds, chemicals, equipment, software, or other inputs—has enabled farms to maintain productivity despite changing production environments (Zilberman et al., 2012; MacDonald et al., 2013). For example, farmers are using more-precise weather and wind-speed forecasts to help in making timely fertilizer, pesticide, and irrigation water applications. In some growing regions, farmers may be able to adopt more-efficient irrigation equipment or controlled drainage. Although this report focuses on adoption of drought-tolerant corn, farmers could adopt other stress-resistant varieties or seed treatments.

Similarly, adoption or increasing use of conservation practices can limit downside production risks while improving environmental outcomes from crop farming. Conservation tillage (including no-till practices) has increased somewhat on U.S. corn fields in recent years (Claassen et al., 2018). Apart from time savings and reduced energy costs, these practices increase the amount of crop residue left on the field, which provides a cover that helps retain water in soils. Benefits from conservation tillage are complemented by adding less water-intensive and higher residue crops, like winter wheat, into rotation with corn. Farmers can receive technical and financial assistance for several of these conservation practices through various Government programs, including USDA's Environmental Quality Incentives Program (EQIP). More generally, participation in EQIP and USDA's Conservation Reserve Program (CRP) can help farmers adapt to local drought risk (Wallander et al., 2013).

Last, use of certain financial management practices, while not *physical* responses to stresses, can ensure that farms reduce their exposure to variability in crop revenue and other farm income. For example, enrollment in Federal crop insurance is a common practice. In the event of eligible drought-related losses, enrolled farmers receive indemnity payments. Further, farmers with share-rented cropland leases could attempt to adjust their leases' terms and conditions to account for yield losses or crop failure from drought. And over longer planning horizons, some farmers might consider scaling up or diversifying their operation as a kind of natural hedge. Each of these, however, has its own set of constraints, so their suitability will vary across farms.

—continued

Crop Farmers’ Strategies to Partially Limit Drought Damages or Increase Resilience to Drought—continued

Production practice	Impacts of practice	Regional availability or feasibility
Adjust planting dates	Avoid high summer temperatures	Limited due to narrow planting windows and possibility of early frozen soils or late freezes
Use more-precise local weather predictions	Enhance information and awareness	Limited in areas with poor broadband connectivity
Adopt stress-resistant seeds	Reduce drought stress	Not widely available for all crops
Adjust row spacing and/or seeding rates	Reduce competition with crop and weeds	Broadly available but limited by field characteristics and impacts on yields
Adjust crop rotations to include less water-intensive and more higher residue crops and/or cover crops	Avoid high temperatures and moisture deficits	Broadly available but limited by soil and field characteristics
Adopt conservation tillage	Avoid high temperatures and moisture deficits	Broadly available but limited by soil and field characteristics
Increase soil organic matter	Avoid moisture deficits, among others	Broadly available but may take time to see benefits
Establish windbreak	Conserve soil moisture	Broadly available but removes some cropland from production
Enroll in Federal conservation programs	Reduce vulnerability to drought and other stresses	Availability varies by region and some field characteristics
Adjust timing, quantities, or rates of fertilizer application	Limit nutrient leaching and runoff after intense rainfall	Broadly available but limited by soil and field characteristics
Increase irrigation water applications or install more-efficient irrigation equipment	Avoid high temperatures and moisture deficits	Limited availability due to limited groundwater and/or surface water
Install/upgrade controlled drainage	Ensure optimal levels of water available to crop	Broadly available but limited by soil and field characteristics
Increase scale or diversify the locality of operations	Increase overall resiliency to several stresses	Limited due to farm budget constraints and competitive land markets
Enroll in Federal crop insurance	Limit income reductions due to yield or revenue loss	Broadly available to eligible producers of certain crops
Adjust terms and conditions of cropland lease	Limit income reductions due to yield loss	Feasible across seasons but “locked in” within a specific growing season

Note: This table is meant to provide a brief description of well-known examples and is not an exhaustive list of all practices available to crop farms.

Source: Adapted from Malcolm et al., 2012.

Crop Rotations and Cover Cropping

Unharvested crop residues are a protective barrier against the physical elements and decompose into organic matter. Different crops that are commonly grown in rotation with corn leave behind different levels of residue. Perennial crops like hay provide nearly complete coverage of the field and leave behind large amounts of residue. Corn and sorghum produce large amounts of residue when they are harvested for grain, but they leave behind far less residue when harvested for silage. Cotton and soybeans provide low amounts of residue (e.g., Claassen et al., 2018).

Because crop rotations affect soil moisture retention, we explore whether drought-tolerant (DT) corn adoption rates vary by prior crop choice (fig. 7).[17] In particular, rotations with certain high-residue crops, with their improved soil moisture retention, might naturally complement DT corn's improved water absorption. For example, 36 percent of fields planted in 2015 to hay other than alfalfa—a high-residue crop—were planted with DT corn the following spring. Roughly 18 percent of fields planted in 2015 to corn—another high-residue crop—were planted with DT corn in 2016. However, we observe similar trends for rotations including low-residue crops. For example, 22 percent of 2015 soybean fields were planted with DT corn in spring 2016. And 49 percent of 2015 cotton fields were planted with DT corn the following spring. The differences in percentages among the four crops are not statistically significantly different.

DT corn is also rotated with wheat, another high-residue crop, but the prevalence of this rotation depends on the type of wheat. For example, around 20 percent of fields growing winter wheat in fall 2015 were planted with DT corn in spring 2016. In contrast, only 2 percent of 2015 spring wheat fields were planted with DT corn in the 2016 season, which is statistically significantly lower than the percentage of fields growing winter wheat in fall 2015 and planted with DT corn in spring 2016.[18] This reflects the fact that spring wheat and corn are not commonly rotated (USDA, ERS, 2017).

DT corn adoption is higher on fields that were planted with soybeans in 2015 than fields planted with spring wheat and certain other crops (fig. 7). It is unclear whether this variation is predominately driven by differences in crop residue or climate, however.[19] For instance, the fact that DT corn adoption rates are relatively high in corn-cotton rotations may be because corn-cotton rotations are common in some parts of Texas, which is also a drought-prone State.

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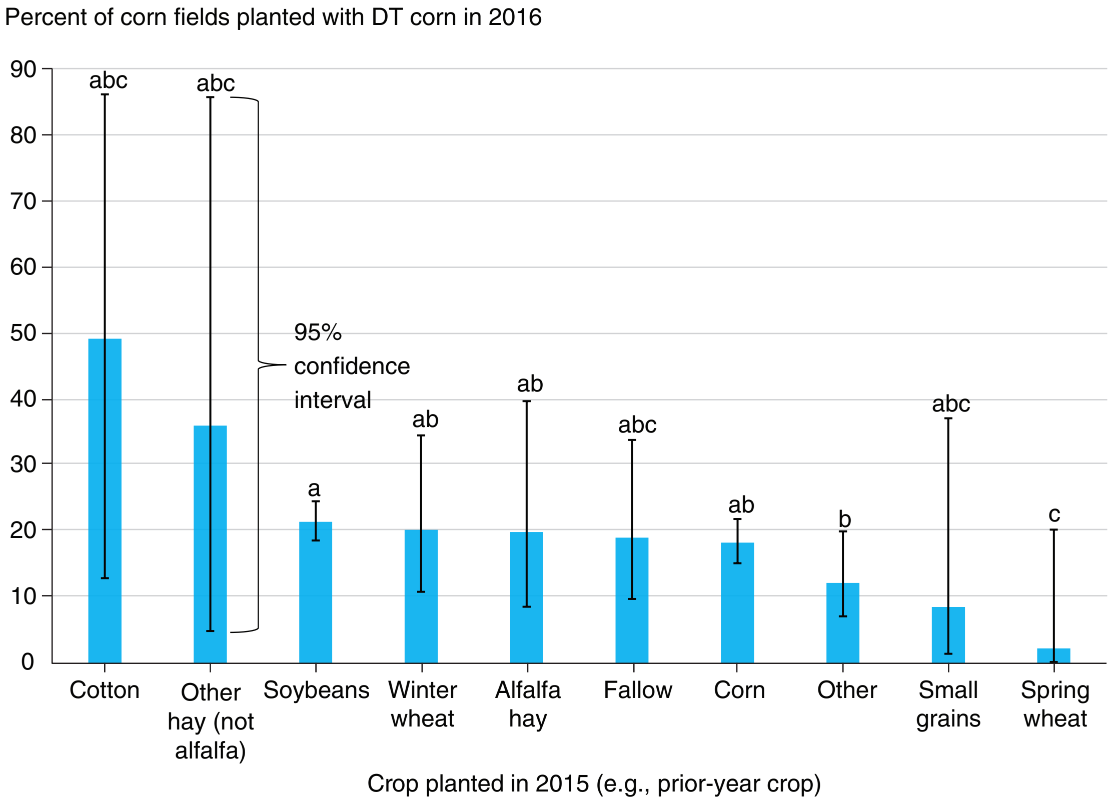
[17] Alternatively, we could examine DT corn adoption rates by crop rotation. Because the target crop of the 2016 ARMS Phase II survey was corn, as is the focus of this report, these recent crop histories can be conceptualized as simple "other crop-corn" rotations.

[18] Much of the winter wheat (2015)-DT corn (2016) rotation acreage was planted in the southern United States, with Kentucky, Missouri, and Texas accounting for just under 30 percent of acreage in these rotations. This rotation is possible because corn can be planted earlier in the South.

[19] Relative crop prices are expected to be important determinants of farmers' crop rotations and their decisions to plant DT corn. For example, periods of high relative corn prices are positively correlated with increased corn acreage and expansion (Wallander et al., 2011).

Figure 7
Drought-tolerant (DT) corn adoption rates by prior crop choice, 2016



Note: The "small grains" category includes rye, barley, and oats. The vertical bars are logit-transformed 95-percent confidence intervals to account for the lower (0 percent) and upper (100 percent) limits of percentages. See Note to fig. 5 for an explanation about interpretation of 95-percent confidence intervals. Differences in lowercase letters across crops indicate statistically significant differences in means ($p<0.05$). For example, among the fields planted with DT corn in 2016, the fraction of fields planted with soybeans in 2015 (with letter a) differs significantly from the fraction of fields planted with "other" crops (letter b) and spring wheat (letter c) in 2015. The fraction of fields planted with soybeans (with letter a) does not differ significantly from the fraction of fields planted with cotton, other hay, winter wheat, alfalfa, fallow, corn, and small grains (i.e., any other column with letter a).
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Cover crops, such as annual ryegrass or certain types of radish, are another source of surface residue and soil organic matter, and they provide living roots in corn fields between fall harvest and spring planting. As with high-residue cash crops, cover crops increase infiltration and reduce evaporation after the cover crop is terminated. In addition, cover crops can: (1) provide old root channels for crop roots, (2) penetrate hard subsoil layers, giving crop roots deeper access to soil moisture, and (3) increase activity of mycorrhizal fungi, which act as root extensions, thus giving crops greater access to soil moisture (Chen and Weil, 2011; Galvez et al., 1995; Williams and Weil, 2004). However, cover crops remove soil moisture and increase transpiration rates while they are growing. If the loss of soil moisture while the cover crop is growing can be made up during the cash crop's growing season, then the cover crop can provide soil-moisture conservation benefits. As with high-residue crop rotations, the potential moisture-conserving impacts of cover cropping could increase the moisture-absorption benefits from DT corn.

Cover cropping remains uncommon but is being increasingly used in corn production. In 2016, 7 percent of DT corn fields were cover-cropped, which is not statistically significantly different from the 10-percent share of non-DT corn fields that were cover-cropped in 2016.

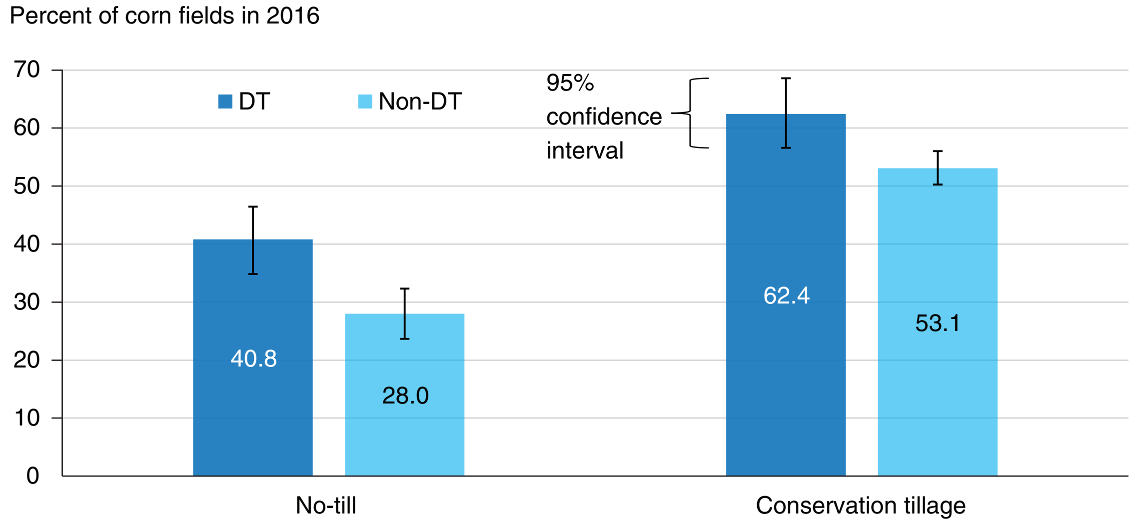
Conservation Tillage

Tillage incorporates residue into the soil, reducing the benefits of surface residues for soil moisture conservation. Tillage also aerates the soil, which increases the decomposition of organic matter. In part, this is why conservation tillage—tillage systems that leave at least 30 percent of the crop residue on the soil surface—has a longer history of use in drier States like Nebraska and Kansas than other regions in the Corn Belt. Both conservation tillage and no-till—a conservation tillage practice in which farmers do not till and, therefore, minimize soil disturbance—have been increasing in recent decades. No-till practices were adopted on only 7 percent of U.S. corn acres in 1988 (USDA, ERS, 1993). However, no-till adoption has increased substantially since that time, especially in semi-arid States such as Nebraska and Kansas (Claassen et al., 2018).

Conservation tillage makes more water available to corn by reducing evaporation. In addition, continuous no-till (i.e., the absence of tillage for several consecutive growing seasons) can increase soils' water-holding capacity and infiltration (Dao, 1993; Lipiec et al., 2006; Mahboubi et al., 1993). Drought-tolerant corn can increase the water taken up by plants and reduce water lost through evapotranspiration (see box, "How Do Drought-Tolerant Corn Hybrids Work?"). Perhaps because these functions are synergistic, DT corn is commonly used in conjunction with conservation tillage (fig. 8). Conservation tillage is used on 62 percent of DT corn fields, compared to 53 percent of non-DT corn fields. This difference is larger for no-till practices: nearly 41 percent of DT corn fields were not tilled in 2016, while only 28 percent of non-DT fields were in no-till.[20] The differences between DT and non-DT fields for both measures of conservation tillage are statistically significant. Among States with the highest rates of DT corn adoption, like Nebraska and Kansas, roughly 73 percent of DT corn fields used no-till practices.

[20] Fields are considered to be managed using conservation tillage if there was at least 30 percent residue cover on the field after planting. Our results are qualitatively similar if we instead classify fields managed using conservation tillage as those with a Soil Tillage Intensity Rating (STIR) of less than 80. The STIR is an index representing the type and severity of disturbance caused by tillage operations (Claassen et al., 2018).

Figure 8
No-till and general conservation tillage practices on drought-tolerant (DT) and non-DT corn fields, 2016



Note: A field is considered to be no-till if at no point during normal field operations were plows or disks, packers, bedders/shapers, cultivators, harrows/drags, land plane levelers, laser planers/levelers, or other miscellaneous tillage equipment used. Fields are considered to be managed using conservation tillage if there was at least 30 percent residue cover on the field after planting. The vertical bars are logit-transformed 95-percent confidence intervals to account for the lower (0 percent) and upper (100 percent) limits of percentages. See Note to fig. 5 for an explanation about interpretation of 95-percent confidence intervals.
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Irrigation

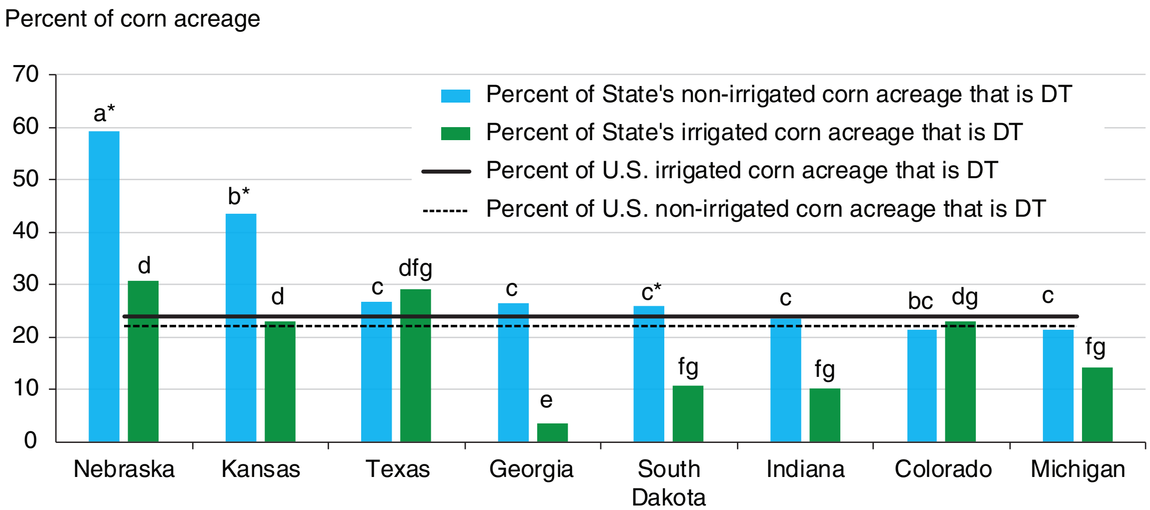
Farmers in some areas can increase soil moisture through irrigation, but they must have access to either surface or groundwater for irrigation to be a viable option. In several areas of the Corn Belt, irrigation is unnecessary, unavailable, or would require investing in irrigation equipment that is not cost-effective. However, in some semi-arid climates, irrigation of corn is quite common: over 60 percent of 2016 corn acres in Nebraska and Kansas were irrigated. Irrigation is also common in more humid areas of the United States, such as Georgia, and can increase yields on rainfed operations in sub-humid and humid areas (USDA, NASS, 2014).

The majority of drought-tolerant corn is non-irrigated (fig. 9). However, even irrigated fields can experience shortages of soil moisture in drought years. Physical, economic, and regulatory constraints can limit the amount of water available for irrigation use.[21] For example, the capacity of the water pump, depth to water table, and size of the field can make it difficult for farmers to maintain adequate soil moisture—especially under hot and dry conditions. Under severe droughts, water tables can decline to such a degree that irrigation is too costly or, in more extreme circumstances, the farmer's well is no longer deep enough to provide adequate groundwater for full irrigation.

[21] Regardless of physical constraints, farmers who have "junior" water rights (as opposed to "senior" or first rights)—mainly for farms in the western and southwestern United States where there is a legal-based system of water allocation—may be barred from irrigating during times of water shortages.

Figure 9

Percent of irrigated and non-irrigated corn acreage planted with drought-tolerant (DT) hybrids for selected States, 2016



Note: Data from the 2016 Agricultural Resource Management Survey were insufficient to determine the use or extent of supplemental irrigation. Asterisks indicate that, for a given State, the share of non-irrigated corn acreage that is DT differs significantly ($p<0.05$) from the share of irrigated corn acreage that is DT. For example, 59 percent of Nebraska's non-irrigated corn acres are planted with DT hybrids (letter a), which is significantly higher than Kansas' share of non-irrigated corn acres planted with DT hybrids (letter b). Within each State, the share of irrigated DT acreage differs significantly from the share of non-irrigated DT acreage (denoted by a*, b*, and c*).
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Adoption rates of DT corn on irrigated fields are highest in areas of the western Corn Belt (Nebraska and Colorado) and southern Great Plains (Kansas and Texas). Roughly 29-31 percent of irrigated corn acres in Nebraska and Texas were planted with DT hybrids in 2016, and 23 percent of irrigated corn acres in Kansas and Colorado were DT. However, these percentages are not statistically significantly different among these four States. Irrigated regions in these States—especially in Kansas and Texas—have relatively lower rainfall. DT corn adoption rates on irrigated fields in the eastern Corn Belt are statistically significantly lower than in Nebraska and Kansas. For example, 10 percent of irrigated corn acres in Indiana and 14 percent of irrigated corn acres in Michigan were planted with DT hybrids.

There was no meaningful difference in per-acre irrigation rates between DT and non-DT corn fields across the United States in 2016. Irrigators applied 10.9 inches of water per non-DT corn acre and 12.9 inches per DT corn acre, but these irrigation rates were not statistically distinguishable.[22] These irrigation rates are comparable to the national rate of 10.7 inches of water per acre of corn from the 2010 ARMS, the most recent ARMS survey of corn fields prior to the 2016 survey. Irrigation rates are influenced by volume and timing of rainfall throughout the growing season and type of irrigation management, among several other factors (Mounce et al., 2016; Zhao et al., 2018).

[22] These rates are also comparable to average irrigation rates reported in NASS's Farm and Ranch Irrigation Survey. For example, the average groundwater irrigation rate in 2013 for all crops in our 19-State sample was 9.7 inches of water per acre. The average onfarm surface water application rate was 9.7 inches of water per acre, while the average off-farm surface water application rate was 11.5 inches of water per acre (USDA, ERS, 2018).

Structural and Productivity Characteristics of DT Corn Fields

Performance of drought-tolerant corn on commercial farms across the United States has not been exhaustively studied. This report examines how certain structural and field productivity characteristics vary by drought-tolerant (DT) corn and irrigation use. These trends are intended to shed light on meaningful differences in characteristics between DT and non-DT corn fields but should not be considered as causal effects. These characteristics, such as yield and yield goals, insurance adoption, land tenure, seeding rates, soil types, and slope types, all contribute to the potential profitability of corn production.[23]

By examining how these characteristics differ between DT and non-DT fields, we gain insights into potential economic drivers and implications of adoption. For example, a greater fraction of DT corn fields have Federal crop insurance coverage than non-DT fields. This might suggest that some farmers view DT corn as riskier than non-DT corn. Alternatively, this might suggest that some farmers are choosing to plant DT hybrids on fields with greater risk or it might simply signal that some farmers do not view drought tolerance as a sufficient hedge against drought risk. In this example, we do not pinpoint the cause, but we uncover a relationship that has economic implications. Since crop insurance policies are sold at greater rates on DT corn fields than non-DT corn fields, DT corn fields are more likely to receive indemnity payments than non-DT corn fields, on average, in the event of eligible losses.

Corn Yields

In 2016, yields and yield goals (the farmer's target yield for the particular corn field that season) were higher on fields planted with drought-tolerant corn than on fields planted with non-DT corn (table 1). On non-irrigated fields, DT corn yields were 6 bushels per acre (or 4 percent) higher than non-DT corn yields, on average, though this difference is statistically insignificant. Average DT corn yield goals on these non-irrigated fields were 8 bushels per acre (or 5 percent) higher than average yield goals on non-DT fields, which is a statistically significant difference. This suggests that farmers who planted DT corn may have expected higher yields than farmers who did not plant DT corn. On irrigated fields, there was no difference in yield goals, regardless of whether DT seeds were planted—perhaps because irrigators expected that drought damages could be offset by irrigation. However, yields were statistically significantly higher by 20 bushels per acre (11 percent) on irrigated DT corn fields than on irrigated non-DT corn fields.

These differences in average yields between DT and non-DT fields, as well as differences in average yield goals, are not necessarily causal. Farmers with higher yield goals tend to apply more inputs, such as fertilizers and pesticides, and make use of more-efficient equipment and/or precision equipment. Farmers with higher yield goals may also use other practices to mitigate the impacts of negative weather and pest shocks (e.g., certain crop rotations and tile drainage). More indirectly, DT corn adopters may also have greater managerial ability, leading them to simultaneously adopt DT corn and one or more of the above practices that jointly increase yields.

[23] The "Field Characteristics" section of the ARMS questionnaire contains a question asking farmers about their "yield goal at planting" for the randomly selected field. For this report, farmers' yield goals are a self-reported target and are not intended as a performance metric.

Table 1

Average yield and yield goals by irrigation use and drought-tolerant (DT) corn adoption, 2016

	DT corn	Non-DT corn
	Bushels/acre	
Yield, irrigated fields	202 (5.56)	182 (5.22)
Yield, non-irrigated fields	155 (4.85)	149 (1.86)
Yield goals, irrigated fields	208 (6.29)	208 (3.34)
Yield goals, non-irrigated fields	167 (2.87)	159 (1.56)

Note: Yield goals are the farmers' yield goals at planting time. The Agricultural Resource Management Survey asks farmers for yield goals for their field and for realized yields. Delete-a-group jackknife standard errors are in parentheses.

Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Yields and yield goals are also constrained by field and soil characteristics largely beyond the farmers' control, including soil type, soil particle size and porosity, acidity, field slope, and other determinants of fertility.

Most U.S. corn-growing regions did not experience significant drought during the 2016 growing season.[24] However, these yield differences are within the range of causal effects found in field trials and other carefully controlled studies that analyze DT corn yields under adequate water conditions.[25] Combining data from 8,725 onfarm strip trials across the United States conducted in 2011-13, Gaffney et al. (2015) show a 1.9-percent DT yield advantage under favorable environments.[26]

Farm and Field Characteristics of Adopters and Nonadopters

There are not many statistically significant differences in structural characteristics between DT and non-DT corn fields (table 2). Both types of fields were located on farms with similar corn enterprise sizes. For example, median corn acreage on DT-corn-adopting farms is 390 acres—only slightly larger than median corn enterprise size for the fields in our sample not planted with drought-tolerant corn. Absence of a size trend is counterintuitive since: (1) large farms tend to be early adopters of new technologies (i.e., Wozniak, 1987), and (2) farms tend to be larger where drought—and DT corn adoption—is more prevalent.[27]

[24] There are two exceptions. South central Iowa and Ohio experienced abnormally dry to moderate drought conditions between June and mid-August 2016. Western South Dakota experienced moderate to severe drought, including some areas of extreme drought, between June and late August 2016 (U.S. Drought Monitor, 2017).

[25] Some studies find no evidence of statistically significant differences in yields between DT and non-DT corn under adequate water conditions (e.g., Zhao et al., 2018). Other studies find a 6- to 7-percent DT yield advantage under moderate water-limited conditions (e.g., Adee et al., 2016).

[26] That study defines environments in which mean yield of the hybrids exceeded 11.4 Mg/ha as "favorable."

[27] Farmers' risk preferences may also help to explain the absence of a size trend. This explanation assumes that DT corn is a risk-mitigating technology and that operators of small farms tend to be relatively risk averse (e.g., Feder, 1980). The higher likelihood of adoption of a new technology on large farms—other things equal—could be offset by the higher likelihood of adoption on small farms due to risk aversion.

Table 2

Structural and productivity characteristics of drought-tolerant (DT) and non-DT corn fields, 2016

Characteristic	DT corn fields	Non-DT corn fields
Corn acreage on farm (acres)		
25th percentile	154	110
50th percentile	390	300
75th percentile	700	704
90th percentile	1,350	1,400
Mean fraction of fields covered by Federal crop insurance (%)	84.3	75.7
	(3.1)	(1.4)
Federal Catastrophic (CAT) crop insurance coverage	13.2	9.2
	(2.6)	(0.8)
Yield protection	8.9	11.4
	(1.6)	(1.5)
Revenue protection	44.5	41.4
	(3.4)	(1.7)
Field ownership structure (%)		
Owned	52.1	55.7
	(3.6)	(1.7)
Rented for cash	33.6	34.0
	(3.4)	(1.5)
Rented for share of crop	13.2	9.0
	(2.5)	(0.7)
Mean per acre cash rent for cash-rented field ($)	131.6	133.4
	(9.42)	(4.08)
Mean landlord's share of crop for share-rented field (%)	38.5	41.2
	(2.4)	(0.8)
Mean row width for field (inches)	30.2	30.2
	(0.19)	(0.10)
Mean seeding rate (kernels/acre)	30,502	31,212
	(229.91)	(93.85)

Note: Yield protection and revenue protection insurance above do not include fields for which Supplemental Coverage (SCO) was purchased. Delete-a-group jackknife standard errors are in parentheses.

Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Similarly, there are few statistically significant differences in certain measures of ownership structure among DT and non-DT fields. In principle, DT corn adoption rates could vary with land tenure based on farmers' risk preferences and the degree and type of risk sharing implicit in crop-sharing agreements. Roughly equal proportions among DT and non-DT fields are owned and rented for cash. However, a larger percentage of DT fields are rented for a share of the crop (13.2 percent) than non-DT fields (9 percent), which is a statistically significant difference. Mean cash rents on cash-rented fields, as well as average landlord's share of the crop from share-rented fields, do not differ between DT and non-DT fields.

Yet, there are statistically significant differences in some risk-management practices based on seed technology type.[28] First, over 84 percent of DT corn fields are covered by Federal crop insurance, compared with 76 percent of non-DT fields. But there are not statistically significant differences in the type of insurance purchased (e.g., yield protection, revenue protection, or catastrophic risk protection). Second, average seeding rates on DT fields are 710 kernels per acre lower than on non-DT fields. Farmers may choose lower seeding rates on DT fields as a risk-reducing strategy (Cooper et al., 2014). Lower plant population densities may help reduce yield losses during drought while conserving yield potential in case of adequate moisture conditions. However, differences in seeding rates may be due to differences in dealers' recommendations, seed prices, or soils and climates in regions where DT corn adoption is higher.

These two differences in risk management between DT and non-DT fields are clearly related to the geography of adoption. DT corn tends to be planted in States with riskier corn production environments (figs. 3 and 4). Greater Federal crop insurance uptake and lower seeding rates are prevalent in these States. [29]

Soils and other physical field characteristics directly influence water and nutrient uptake, thus potentially influencing farmers' decisions to plant DT corn. Sandy soils, for example, are better drained and retain less moisture than clay soils. Steeply sloped land and highly erodible soils tend to be less productive because substantial quantities of nutrients and water can run off the field without reaching the crop. However, the extent to which these soil and field characteristics tend to increase or decrease yields is influenced by the use of irrigation. We find some significant differences in DT adoption rates between irrigated and non-irrigated corn across these field characteristics (table 3).

For all fields, the fraction of corn fields planted with DT hybrids is between 14 and 22 percent across primary soil texture types and slope types. The DT adoption rate for irrigated clay soils (53 percent) is higher than for non-irrigated clay soils (21 percent), though this difference is not statistically significant. Adoption on irrigated sandy soils (6 percent) is significantly lower than for non-irrigated sandy soils (24 percent). Irrigated sandy soils tend to have less susceptibility to drought than non-irrigated soils. If farmers view drought tolerance and irrigation as substitutes on well-drained soils, this could explain why adoption rates are significantly lower on these fields.

[28] Farmers' risk aversion may also explain joint risk-management and DT corn adoption decisions. In a simulation study within a developing-country context, Lybbert and Bell (2010) show that diffusion of DT corn generally takes more time among highly risk-averse farmers. Joint marketing of DT corn seeds and drought index insurance in developing countries could reduce farm households' vulnerability to drought if these products are complements (e.g., Lybbert and Carter, 2015).

[29] The 2016 ARMS data show that 94 percent of Nebraska's corn acreage and 90 percent of Kansas' corn acres were covered by Federal crop insurance. Additionally, more than 88 percent of corn acreage was insured in Iowa, Illinois, Texas, North Dakota, Minnesota, and South Dakota. Average seeding rates in Nebraska and Kansas—28,074 and 25,409 kernels per acre, respectively—are significantly lower than the national average seeding rate.

Table 3

Drought-tolerant (DT) corn adoption rates by soil characteristics and field type on non-irrigated and irrigated fields, 2016

Characteristic	DT adoption rate (percent of fields)		
	Non-irrigated fields	Irrigated fields	All fields
Overall	20.2	22.7	20.4
	(1.1)	(4.0)	(1.0)
Soil type			
Primarily loam	20.5	19.7	20.5
	(1.7)	(6.9)	(1.7)
Primarily clay	21.1	53.3	22.1
	(3.9)	(21)	(3.6)
Primarily sandy	24.4	6.2	20.8
	(7.6)	(3.3)	(6.2)
Mixed	19.4	26.6	19.8
	(1.9)	(8.0)	(2.0)
Slope type			
Nearly flat	19.7	18.1	19.6
	(1.9)	(5.0)	(1.7)
Moderately sloped, 3-9% grade	21.2	27.8	21.5
	(1.6)	(6.8)	(1.5)
Steeply sloped, over 10% grade	13.4	d	14.4
	(5.4)	d	(5.5)
Any part of field is highly erodible	25.1	45.2	26.8
	(3.6)	(11.3)	(3.6)
Any part of field contains a wetland	17.5	45.2	25.2
	(7.7)	(17.4)	(7.7)
Field has subsurface drainage	18.9	11.1	18.8
	(1.7)	(7.5)	(1.7)

Note: The moderately sloped category aggregates fields that have even grades and fields that have variable grades. The steeply sloped category also aggregates fields that have even and variable grades. The "d" indicates data are suppressed due to insufficient number of observations. Delete-a-group jackknife standard errors are in parentheses.

Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management Survey.

Use of DT corn is also statistically significantly higher on irrigated fields that are highly erodible or contain a wetland (45 percent).[30] But the adoption rate on irrigated fields with subsurface drainage is insignificantly lower at 11 percent, likely because DT seed use is common in areas where tile drainage is common (e.g., Iowa, Illinois, Indiana, Michigan, Minnesota, and Ohio).

[30] To the extent that highly erodible corn fields have lower soil moisture retention, farmers may want to complement irrigation with use of DT seeds. It is less clear why DT corn adoption is higher on irrigated fields that contain a wetland than on non-irrigated fields, though geography plays a role. Roughly 56 percent of 2016 irrigated fields that contain a wetland are located in Nebraska, the State with the highest DT adoption rate. On the other hand, South Dakota—the State with the lowest DT corn adoption rate—has the highest percentage of non-irrigated fields containing a wetland.

Conclusions

By 2016, approximately 22 percent of national corn acreage consisted of drought-tolerant (DT) corn hybrids. Diffusion of this new technology has been partially driven by farmers' experiences with drought: adoption is highest in semi-arid regions of the western Corn Belt where these seeds were partly developed and where companies' marketing efforts were initially concentrated. The expected benefit from DT corn adoption is likely to be higher in dry or drought-prone corn-producing regions than in regions with ample rainfall. Regardless of region, DT corn hybrids tend to be stacked with genetically engineered (GE) traits (e.g., herbicide tolerance and insect resistance), and farmers tend to jointly adopt DT seeds and moisture-conservation practices (e.g., no-till and conservation tillage) that are beneficial under drought conditions.

The decision to plant DT corn can be likened to farmers' decisions to purchase insurance. Under mild-to-moderate drought conditions, planting DT corn can "pay out" in the form of reductions in drought-induced yield losses. Farmers who adopt DT corn value the expected avoidance of such yield losses at least as much as the premiums they are willing to pay for the DT technology. However, DT seeds provide incomplete protection from drought, and substantial losses could result under severe conditions. Under extreme or exceptional drought, there could be little expected benefit to adoption since both DT and non-DT corn are likely to suffer crop failure. Yet, there remain conditions under which DT corn may be an effective risk-management tool.

Broad policy implications stem from these potential improvements in risk management. Under mild-to-moderate drought conditions, the decision to plant a DT corn hybrid could determine whether a farmer suffers losses that warrant filing a Federal crop insurance claim. Continued diffusion of DT corn and further development of drought tolerance in other field crops could result in cost savings to farmers, private insurers, and the Federal Government through reduced indemnity payments. Similar reductions in drought-related natural disaster payments could also occur under increasing adoption and technological improvements.

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Appendix: Development and Commercialization of DT Corn Hybrids Available in 2016

Following the initial development of its genetically engineered (GE) drought-tolerant (DT) hybrids, Monsanto conducted field trials from 2002 to 2008. Many of the initial field trials were conducted in the western Corn Belt and Great Plains from 2002 to 2005. Later field trials were held in major corn-producing regions of the United States and Chile in 2006 and 2007. These trials compared the performance of DT hybrids to conventional (non-DT) controls across irrigation treatments. They found no significant difference in yields between the GE DT corn and conventional controls under well-watered conditions, though the DT plants experienced less yield loss under water-limited conditions (i.e., 20 percent less than normal water conditions) (Pester et al., 2009).

The U.S. Food and Drug Administration (FDA) deregulated Monsanto's DT corn in December 2010. One year later, USDA's Animal and Plant Health Inspection Service (APHIS) also granted deregulated status, finding it would be unlikely to present plant pest risks (Pester et al., 2009; USHHS, FDA, 2010; USDA, APHIS, 2011). Note that these agencies have distinct regulatory roles: FDA ensures that foods from GE plants are as safe as foods from conventionally bred plants, while APHIS ensures that GE plants do not pose plant pest risks.

Unlike the genetically engineered DT trait, non-GE drought-tolerance traits are not assessed within the U.S. biotechnology regulatory framework. Consequently, non-GE DT hybrids can be commercialized relatively quickly. However, the research and development (R&D) leading to commercialized non-GE DT hybrids remains costly and technically challenging.

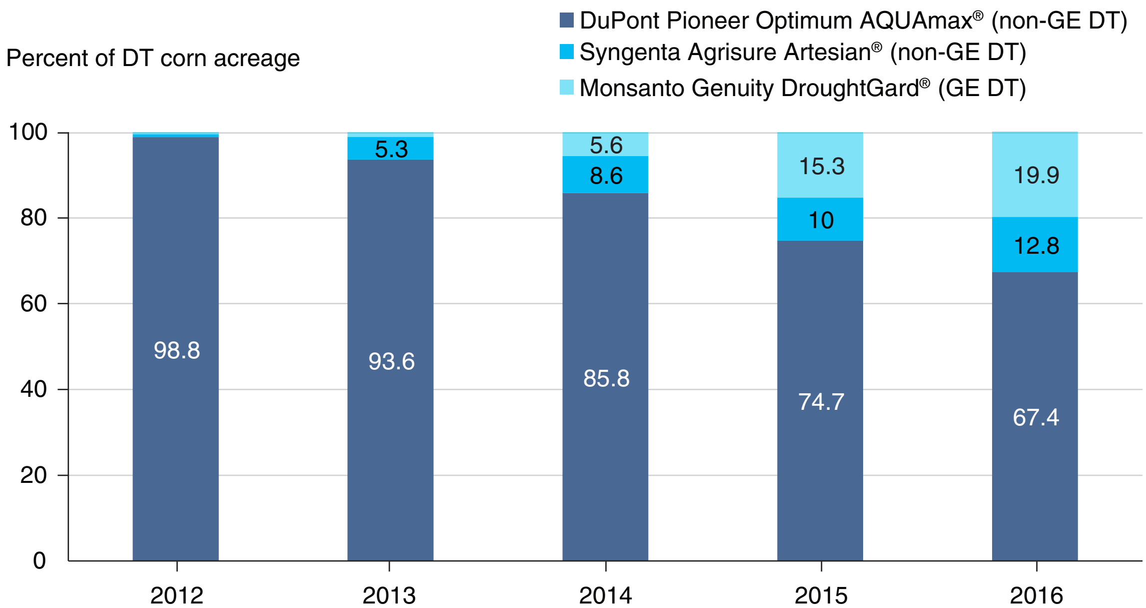
Some improvements in drought tolerance have occurred as a result of conventional breeding and selection for overall yield increases. For example, certain commercially successful hybrids introduced into U.S. markets between 1953 and 2001 have shown gradual yield increases under drought conditions because of improvements in reproduction timing (e.g., greater synchronization between pollen shed and silk emergence) and increases in the number of kernels per ear and kernel weight (Campos et al., 2006). This "indirect" knowledge from conventional breeding has been a useful input into DT corn development.

The non-GE DT hybrids available as of 2016 have been developed using molecular breeding, or the application of molecular biology to plant breeding. First, initial field trial data from small-plot experiments in California, Chile, and other locations were analyzed to identify promising hybrids. Next, the genetic makeup of these hybrids was analyzed by introducing variations (i.e., genetic markers) in certain parts of DNA molecules at known locations. Analyses of the plants' physical traits and genetic makeup were ultimately used to generate predictions about which hybrids would be most drought tolerant and have other desirable traits. Finally, select hybrids were field-tested in further evaluation and validation stages for several years. A subset that performed favorably and met certain criteria (e.g., lack of severe yield penalties in the absence of moisture stress) were commercialized (Heffner et al., 2009; Gaffney et al., 2015).[31]

[31] Information about the exact scope and timing of the R&D leading to commercialized DT corn hybrids is not publicly available. However, Monsanto filed for patent protection on "methods for enhancing drought tolerance in plants and compositions thereof" in September 2004 (Fernandes, 2010). Regarding non-GE drought tolerance, DuPont Pioneer has applied for at least 10 patents related to drought tolerance in plants since 2007. Similarly, Syngenta has applied for at least five patents related to drought tolerance in plants since 2010.

Differences in product development timing, seed companies' regional marketing strategies, seed pricing, and farmers' local growing conditions and management practices have resulted in the current DT seeds market structure (fig. A-1). Non-GE DT seeds represented 99 percent of DT corn acreage in 2012. This is largely because non-GE DT seeds were commercially introduced a year before GE DT seeds, although a more expansive national marketing strategy may also have played a role. The share of GE DT seeds has steadily increased since 2012. By 2016, GE DT seeds constituted no more than 20 percent of DT acreage. A relatively slower product launch and premiums for the transgenic DT trait partially explain the lower market share for GE DT seeds (Minford, 2015).[32]

Figure A1
Drought-tolerant (DT) corn market (acreage) shares of top three firms selling DT corn hybrids between 2012 and 2016



Note: Estimates are company shares of DT corn acreage, not company shares of the entire U.S. corn acreage. For purposes of this report, "GE DT" corn refers to hybrids with genetically engineered drought tolerance, while "non-GE DT" corn refers to hybrids with conventionally bred drought tolerance. To our knowledge, Monsanto was the only major producer of corn seeds with drought tolerance from genetic engineering between 2012 and 2016.
Source: Estimates use data from: Kathy Graul, "DuPont Pioneer doubles amount of AQUAmax drought-tolerant corn hybrids for 2013," Farm Industry News (February 28, 2013); Mike Minford, "Farmers Test Drought-Tolerant Corn Hybrids," Corn + Soybeans Digest (January 23, 2015); Karl Wolfshohl, "Weather Beaters," Progressive Farmer (December 2015); Andrew Thompson and Caroline Copley, "Syngenta says drought-hardy corn did well in U.S.," Reuters (September 12, 2015); Syngenta AG, Annual Review 2013; Monsanto Company, "Western Great Plains Growers Gearing up to Plant Monsanto's New DroughtGard Hybrids," Press Release (February 21, 2012); personal communications with Duane Martin (at Syngenta) and Thomas Eickhoff (at Monsanto); and DuPont Pioneer, 2017 AQUAmax Sell Sheet.

[32] These market shares are likely to evolve as farmers gain more experience with DT corn and seed companies release new hybrids. For example, Dow AgroSciences released a version of stress-tolerant hybrids under its Mycogen seed brand in mid-2015. Bayer's Crop Science division has researched genes to reduce drought-caused tissue and DNA damage, though it is unclear if this research will be applied to corn (Edmeades, 2013).

It is unknown what the impacts of recently settled and ongoing mergers in global seed and agricultural chemical markets will be on future R&D and subsequent adoption of DT corn. In part, this is because of the complex legal and business interrelationships between major agricultural input companies (MacDonald, 2017). For example, as part of its acquisition of Monsanto, Bayer has been required to sell its glufosinate ammonium business (i.e., Liberty® herbicides) to a competitor, BASF—a German-based chemical firm (United States v. Bayer AG and Monsanto Company, 2018). Monsanto collaborated with BASF to develop its Genuity DroughtGard® DT seeds. Currently, some of Syngenta's Agrisure Artesian® DT seeds—and possibly those of other companies—are bundled with tolerance to these herbicides (i.e., LibertyLink® seeds). Since Syngenta was acquired by ChemChina in 2017, longer term R&D investments into these DT seeds and competing products are unclear. However, future innovations in drought tolerance can be expected if multiple input companies continue to compete for profitable future sales (Shapiro, 2012).

To date, the international research community has released hundreds of varieties of DT corn suited to growing environments outside the United States. The Drought Tolerant Maize for Africa (DTMA) project (2007-15), an international partnership, developed and introduced at least 233 DT corn varieties across 13 Sub-Saharan Africa countries.[33] As a fraction of corn acreage, the countries with the highest DT adoption rates in 2013-14 were Nigeria (23 percent), Benin (22 percent), and Malawi (22 percent) (Abate et al., 2015). In Nigeria, average yields of DTMA DT corn adopters were 12.6 percent higher under mild droughts than nonadopters during 2014-15 (Wossen et al., 2017). The Water Efficient Maize for Africa (WEMA) project (2013-18) is a large public-private partnership between the International Maize and Wheat Improvement Center (CIMMYT), Monsanto, and five Sub-Saharan countries. Unlike DTMA releases, some WEMA varieties have GE DT traits (Oikeh et al., 2014). A successor is the Stress Tolerant Maize for Africa project (2016-20), which intends to develop 70 corn varieties with resistance to various stresses, including drought (Abate et al., 2017).

[33] Corn plants in the United States are hybrids, the result of crossing two inbred lines. In contrast, nearly 37 percent of the DT varieties released under DTMA as of January 2016 were open-pollinated varieties (OPV) (Abate et al., 2015). Farmers in developing countries adopt OPVs for several reasons, including accessibility and expense of hybrids relative to OPVs (Edmeades, 2013).