Chapter 2

Corn Productivity: The Role of Management and Biotechnology

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Abstract

The last few decades have seen a rapid increase in corn production, making corn the most important cereal in the world. This evolution is due in large part to rapid productivity growth for corn. Both improved genetics and improved farm management have contributed to large increases in corn yield. The paper reviews how genetics, biotechnology and management have interacted to increase agricultural productivity and reduce farm risk exposure. It documents the stellar performance of corn in terms of productivity growth. It also discusses the recent evolution of corn markets and evaluates the prospects for the future.

Keywords: corn, productivity, biotechnology, risk, management

1. Introduction

Corn (*Zea mays*), also called maize or field corn, is the most important cereal in the world, with annual global production exceeding that of wheat and rice. In 2017, corn production accounted for 41% of total grain production in the world [1]. While corn is a staple food in parts of the world, it has many uses, including animal feed, biofuel and sweetener. This chapter provides an overview of the evolving role of corn in agriculture.

Corn was first domesticated in southern Mexico about 9000 years ago [2, 3]. Its closest wild relative is teosinte, a wild grass of Mexico, Guatemala and Honduras. A major puzzle is the great genetic differences between teosinte and corn, indicating how key mutations and human selection contributed to genetic evolution [4]. After the Columbian exchange, corn production spread throughout the world. Corn is a highly productive crop with the ability to exploit available soil nutrients. As a C4 plant, corn has some photosynthetic advantages in capturing solar energy in warm weather compared to C3 crops such as wheat, rice and soybean. Due to its high productivity under various climate conditions, corn is now the largest grain crop in the world [1]. Favorable agro-climatic conditions in the US "Corn Belt" have made the US the largest corn producer. In 2017, corn production in the US accounted for 35% of world corn production [1].

The rise of corn as the most important cereal in the world has been associated with important improvements in its productivity [5]. **Figure 1** illustrates the evolution of the average corn yield on US farms from 1870 to 2017 [6]. **Figure 1** shows that corn productivity was basically stagnant before 1940: during the period 1870–1940, US average corn yields stayed within a narrow range between 20 and 30 bu/acre. (between 1200 and 1900 kg/ha)[1] Starting in 1940, a period of fast and steady rise in corn productivity began and continues to this time. US average corn yield increased from 28.9 bu/acre (1.81 metric tons/ha) in 1940 to 176.6 bu/acre (11.1 metric tons/ha) in 2017 [6]. This amazing achievement means that a given area of land can produce 6.1 times more corn in 2017 than in 1940, which corresponds to an average annual growth rate of 2.35%, reflecting the rapid technological progress sustained over the last seven decades. This achievement raises two questions. First, what are the sources of this growth in corn productivity? Second, is it likely to continue in the future? Below, we discuss the role played by two key drivers of corn productivity: improved genetics and improved management. We also consider the corn market and its evolving prices. Finally,

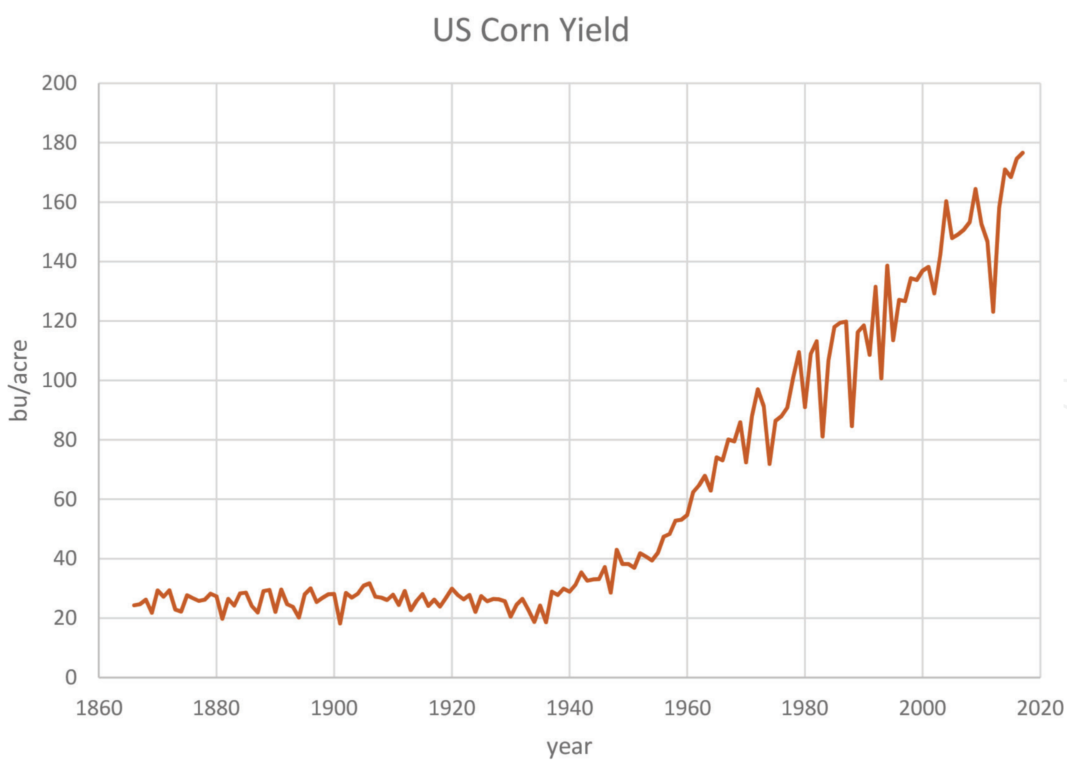

Figure 1. Historical corn yield, US. Source: The corn yield is measured in dollar per bushel, as reported by USDA-NASS [6].

[1] 1 bushel of corn equals 25.40 kg and 1 acre of land equals 0.4047 hectare. Thus, 1 bu/acre = 62.77 kg/hectare.

we reflect on what may come next. Some evidence suggests that agricultural productivity growth may be slowing down, raising concerns about our ability to feed a growing world population (e.g., [7]). We ponder these prospects as they apply to corn production.

2. Corn productivity

Genetic selection has been a very important driver of agricultural productivity. The process started some 9000 years ago in Mexico when corn was first "selected" and evolved from its wild ancestor [2]. Over the centuries, accidental mutations and some intentional selections contributed to beneficial changes [3]. But as **Figure 1** indicates, the rate of genetic improvement was very slow before 1940. Genetic selection was then based mostly on traditional breeding methods trying to combine desirable characteristics of each parent into the progeny. Applied to crops, farmers used selective breeding to pass on desirable traits while omitting undesirable ones. The desirable traits included higher yield and better quality as well as improved adaptation to local agro-climatic and ecological conditions. When applied by farmers, the selection intensity was low, generating slow genetic changes.

The early part of the twentieth century saw the rise of modern genetics and its applications to plant breeding. The discovery of hybrid vigor led to the development of hybrid seed corn and rapid improvements in corn productivity [5, 8]. The higher corn yields stimulated the rapid adoption of hybrid seed corn among US farmers [8, 9]. The new corn hybrids also contributed to the development of a seed corn industry that focused on refined genetic selection [10]. The increased intensity of genetic selection contributed to the development of improved varieties that were better at capturing soil nutrients and more resistant to diseases [5]. As **Figure 1** shows, the result has been decades of genetic improvements and rapid and sustained growth in corn yields.

Starting in the 1980s, progress in biotechnology revolutionized genetic selection. The identification of genes and the refinements in gene transfer[2] technologies opened new opportunities for genetic selection. Eventually, this process led to the development of genetically engineered (GE) corn hybrids that, along with the patenting of GE seeds, stimulated the growth of biotechnology in agriculture. The first GE corn hybrids became commercially available in the US in 1996, with US farmers rapidly adopting the technology. In 2017, more than 90% of all corn planted in the US was GE [12]. The rapid adoption of GE corn in the US led to significant productivity improvements [13]. Over the last two decades, the adoption of GE seed in agriculture has proceeded around the world, though at different rates depending on each country's regulations [14].

Two major types of GE traits are currently available in the hybrid seed corn market: those providing insect resistance (IR) (commercially available in corn in 1996) and those providing herbicide tolerance (HT) (commercially available for corn in 1998). Hybrid seed corn contains these traits either singly or combined as stacks or pyramids, so that a single hybrid is both IR to multiple pests and HT to more than one herbicide.

[2]We now know that horizontal gene transfers across species are not uncommon and that they played an important role in the evolution of life (e.g., [11]).

In the US, currently available IR traits involve gene transfers from the soil bacterium *Bacillus thuringiensis* (Bt) so that hybrids express insecticidal proteins in their tissues that help control specific insect pests. Bt corn hybrids in the US focus on two pests that have had significant adverse effects on corn yield: European corn borer (*Ostrinia nubilalis*) and corn rootworm, a complex of four closely related species (*Diabrotica* spp.). European corn borer larvae feed on corn plant tissues, including tunneling through corn stalks and ear shanks, which not only disrupts plant functions and so causes direct yield loss, but also causes plant lodging and ear drops, causing additional yield loss. Corn rootworm larvae feed on corn roots, which disrupts water and nutrient uptake by the plant and so causes direct yield loss, and also causes plant lodging. Both pests have historically caused significant damage to corn plants, reduced corn yield and are somewhat difficult to control using conventional insecticides [15].

Bt corn has proven more effective in controlling European corn borer and corn rootworm than conventional insecticides, thus increasing harvested yields. In addition, farmer adoption in the US of Bt corn has reduced the aggregate use of insecticides [16]. The rapid adoption of IR Bt corn in the US reflects that US farmers have obtained significant productivity benefits from this technology [12, 13].

HT corn hybrids simplify herbicide-based weed management by allowing application of herbicides on the crop without causing crop damage. Weed management without HT hybrids is managerially more complicated since several weed species look similar when they are small at the time when farmers must make herbicide decisions, but different species commonly require different herbicides for effective control. The earliest and still most popular HT hybrid is tolerant of the herbicide glyphosate, though other types of HT hybrids have been available. As a broad-spectrum herbicide, glyphosate controls a wide range of weed species, so that farmers do not need to know the specific weed species in their fields and which herbicides provide effective control. As a result, farmers rapidly adopted glyphosate tolerant corn hybrids and glyphosate quickly become the most commonly used corn herbicide, with glyphosate used on approximately 75% of US corn acres since 2008 [17]. In US, farmer adoption of HT hybrids has reduced the aggregate use of herbicides [16]. In addition, HT varieties facilitate farmer adoption of reduced tillage and no-till systems, which not only reduces soil erosion, but also lowers labor and fuel requirements [18]. Features such as these have made GE corn attractive to US farmers, contributing to their rapid adoption [12, 13].

3. The role of management

While improved genetics have contributed greatly to increasing corn productivity over the last 70 years, other factors also played a role. Duvick [5] has noted that corn productivity per plant has not changed much over the last few decades, suggesting that, under favorable conditions, the efficiency of photosynthesis for corn (as a C4 plan) has not improved. If so, what is the source of corn productivity growth? Duvick [5] argued that most of the historical increases in US corn yields are due to increases in plant density. Thus, corn productivity gains have come from the interactions between the plant and its environment, along with improvements in farm management and cultural practices. Over the years, new corn hybrids have been selected to be more resistant to lodging and more tolerant of biotic stress (pest damage, weed competition, disease) and abiotic stress (adverse weather, poor soil conditions). These genetic changes have interacted with improved management practices, including fertilizer use, irrigation, tillage system, weed control, pest management and crop rotation. Fertilizer applications remedy soil nutrient scarcity, as corn yield is very responsive to nitrogen [5]. When available, irrigation alleviates soil water scarcity and drought. Pest and weed populations can be (at least partially) controlled and suppressed by tillage, crop rotations and by the use of pesticides (insecticides and herbicides). Crop rotation had been used by farmers for centuries to reduce pest and weed infestation and to restore soil fertility [19–21].

The hypothesis that management and genetic biotechnology interacted in generating recent corn productivity gains have been investigated by Chavas and Shi [22] and Chavas et al. [23]. They found evidence of the important role of management and of interaction effects between technology and management. First, they documented how biotechnology has been a major driver of improved corn productivity over the last decade. They also explored how the benefit of GE traits can vary with agro-climatic conditions. Second, they showed how GE hybrids provide enhanced control of pest damages, thus reducing exposure to both risk and downside risk (the provability of facing low yields). Reducing risk exposure is a major part of the benefits of GE technology [24]. Importantly these GE benefits can go beyond the farm if the suppression of pest population is regional [25]. Third, Chavas and Shi [22] and Chavas et al. [23] showed how crop rotation and GE technology provide alternative ways to control pest populations, indicating that they behave as substitutes in the corn production process. Fourth, they reported the presence of synergy between biotechnology and plant density as they affect corn productivity. By improving pest control, GE hybrids make it possible to obtain greater productivity from higher plant density, evidence that the observed growth in corn productivity has been the outcome of important synergies between genetics and improved management.

4. Corn markets

In a market economy, technological progress affects producers, consumers and prices. **Figure 2** presents the evolution of US corn prices ($/bu) over the period 1947–2017, reporting both nominal prices and real prices [6]. Real prices are nominal prices adjusted for inflation by dividing by the US Consumer Price Index (CPI), in this case with 1983 normalized to 1. **Figure 2** shows that the nominal price of corn has gone from $1.52/bu ($59.8/metric ton) in 1950 to $3.36/bu ($132.3/metric ton) in 2017, corresponding to an average increase of +1.19% per year. It also shows that the real price of corn has gone from $6.30 to $1.37/bu, corresponding to an average decline of −2.25% per year.[3] This sharp decline in real price means that, holding purchasing power constant, an individual can buy 4.6 times more corn in 2017 than in 1950. This dramatic change mostly arises from productivity gains. Indeed, the rate of change in the real corn price (−2.25% per year) almost perfectly matches the rate of change in yield reported earlier (+2.35% per year).

[3] The difference is due to inflation, the average US inflation rate between 1950 and 2017 being +3.44% per year.

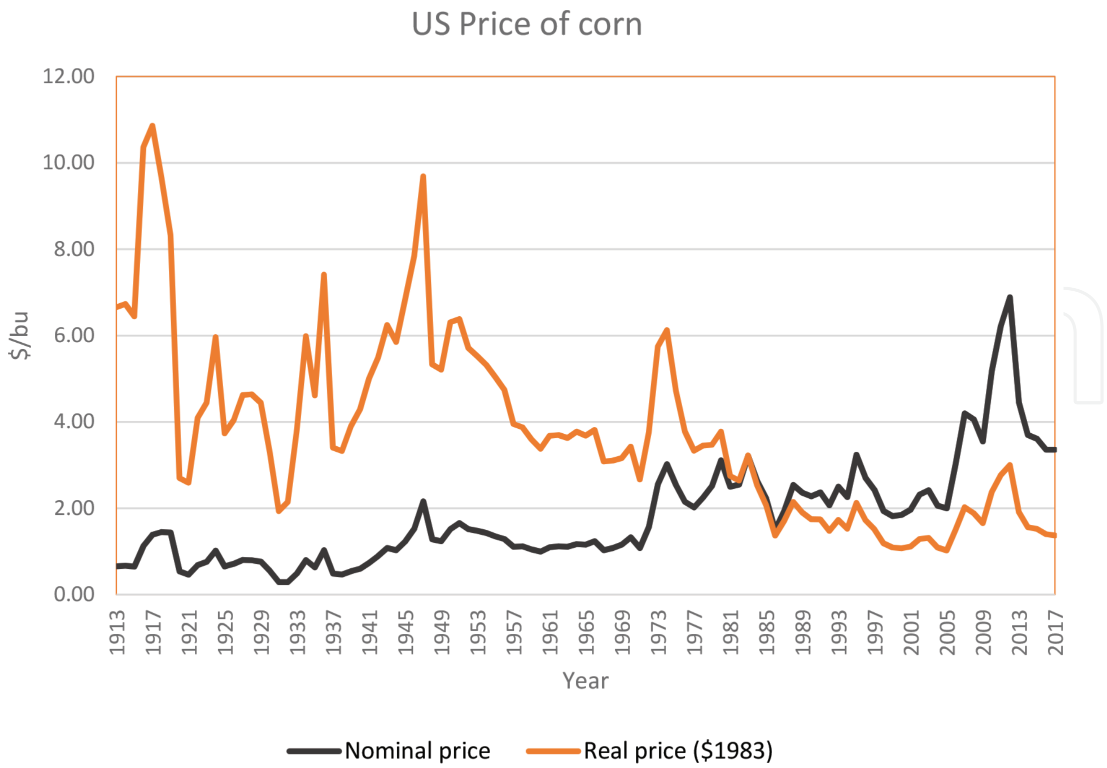

Figure 2. Historical price of corn, US. Source: The nominal corn price is the price received by farmers ($/bu) as reported by USDA-NASS [6]. The real price of corn is the nominal price divided by the consumer price index (*CPI*) as reported by BLS, with $CPI_{1983} = 1$.

In general, technological progress improves the aggregate welfare of society by allowing the production of greater outputs at lower cost (less resource use). But productivity growth can also have important distributional effects. In the corn sector, rapid technological progress has reduced cost and stimulated supply, which in turn has pushed market prices down. As just noted, the observed decrease in real prices reported in **Figure 2** can be attributed in large part to technological progress in the corn industry. It indicates that most of the benefits of productivity gains are actually captured by consumers in the form of expanded quantities produced and lower market prices. As most corn is not directly consumed by people, but used for livestock feed and more recently fuel, these consumer gains arise from lower prices for meat, dairy products, eggs and fuel. But these lower (real) market prices contribute to declining farm revenue.

Interestingly, technological progress in agriculture may not benefit farmers at the aggregate—if the lower output price due to increased productivity generates a decline in revenue that exceeds the reduction in production cost.[4] This process is called the technology treadmill or Cochrane's treadmill after the originator of the theory [27]. Early adopters of new productive technologies benefit by reducing their cost of production, but later adopters will lose if, as supply expands, the output price declines more than the decrease in production costs. The

[4]This can take place when the demand is highly price-inelastic, i.e., when the output price decline is "large enough" to imply a substantial decline in revenue that swamps the decrease in cost. This scenario is relevant as the demand for food in general and for corn in particular tends to be highly price-inelastic (e.g., [26]).

treadmill occurs because, even if farmers in aggregate are made worse off by the new technology, farmers individually still have an incentive to adopt the new technology to reduce their cost of production in a race to outrun the decline in real prices [28, 29].

Globally, about 5% of the calories consumed per person come directly from corn, but this demand varies across countries. In much of Latin America, corn is mostly used for direct human consumption. For example, 33% of the calories consumed per person in Mexico come directly from corn.[5] In the US (and many other countries), corn is used mainly as livestock feed, an important input in the production of meat (beef, pork, and poultry), dairy and eggs. As a result, the demand for corn is a derived demand, with meat, dairy and eggs being the final consumer good.

Corn also has other uses such as for making sweeteners and ethanol. Derived demands for these corn products depend in part on government policy. For example, the US has a protectionist policy toward sugar, so sugar import restrictions have increased the domestic price of sugar [30]. The higher US sugar price has stimulated the search for sugar substitutes in the US, including corn sweeteners. This policy increases demand for corn, with more than 5% of US corn production used for sweeteners, and contributes to a higher corn price, which benefits US farmers but costs US consumers [30].

The US ethanol policy has an even larger impact. The rapid development of the US ethanol industry after 2000 is closely associated with government policies supporting the production of biofuel [31]. Ethanol subsidies, restrictions on ethanol imports and mandates for blending ethanol with gasoline have greatly stimulated the production of corn-based ethanol, leading the US ethanol industry to consume almost one third of US corn production. Over the last 15 years, US biofuel policy has greatly stimulated the demand for corn and affected agricultural markets. Roberts and Schlenker [26] estimated that US ethanol policy has increased world food prices by about 30%. This large effect is due to a price-inelastic demand for food and a diversion of land away from producing feed/food toward producing biofuel. In general, farmers have benefited from higher food prices, but the policy has significant distributional consequences, as consumers pay significantly more for food. Using "consumer surplus" as a measure of consumer welfare, Roberts and Schlenker [26] estimated that US ethanol policy contributed to a loss in world consumer welfare of $180 billion per year. The debate about the economics and policy of corn-based biofuel continues [32, 33].

5. Prospects for the future

Over the last several decades, productivity growth in the corn sector has been stellar, which is good news in a world where feeding a growing world population is challenging. There are current concerns that agricultural productivity growth may be slowing down (e.g., [7, 34]). So far, such concerns do not seem to apply to corn, since US average corn yields continue to climb at a steady rate, and Chavas et al. [13] provide evidence that biotechnology has helped

[5]These estimates from https://www.nationalgeographic.com/what-the-world-eats/ based on UN FAOSTAT data for 2011.

increase corn productivity growth over the last two decades. Despite these continual productivity gains, challenges still exist, chief among them are resistance and climate change.

The stellar productivity gains from commercially applying biotechnology in corn have focused on improving insect and weed management, which has created selection pressure on many pest species to evolve resistance to control. Even if farmers follow resistance management practices, pests have and will continue to evolve resistance—these practices only slow the rate of resistance evolution, they do not stop it.

Western corn rootworm (*Diabrotica virgifera virgifera*) evolved resistance to rootworm Bt corn within a few years of commercial release [35]. Rootworm Bt hybrids still have value to farmers, but their continued use requires that companies pyramid multiple rootworm traits together and that farmers use additional management practices such as crop rotation and conventional insecticides [36]. Companies have also responded by developing alternative GE traits to manage corn rootworm. Potentially the most promising is RNA interference (RNAi), which uses biotechnology so that crops create double-stranded RNA segments that interfere with transcription of specific segments of RNA found in only the target species [37–39]. The first US commercialization of RNAi in corn received EPA approval in 2017.[6] Also, corn has been genetically engineered to express insecticidal proteins from non-Bt bacteria and shows excellent activity for control of corn rootworm larvae [40].

Weed control in corn (as with many crops) is important, with potential yield losses without control exceeding 50% [41]. Over the last few decades, herbicide resistant weed populations have continued to develop and spread globally [42]. HT seeds do not directly cause the development of herbicide resistant weeds, as herbicide resistant weeds have evolved in regions such as Western Australia where HT crops are not used [42]. Rather, HT crops contribute by encouraging farmers to rely on fewer herbicides modes of action and less tillage, which accelerate the development and spread of resistant weed populations [43, 44]. Problems with herbicide resistant weeds continue to develop and spread globally, which is worrisome because no new herbicide modes of action have become commercially available since the early 1990s and weed populations resistant to multiple modes of action having been documented [45, 46]. How weed control in corn and other crops will evolve over the next few decades to address herbicide resistant weeds and the possible role that GE hybrids and biotechnology will play is unclear. The race between insects and weeds and our ability to develop technologies and management schemes will continue to impact agricultural productivity. Maintaining our lead in this race will require R&D investments and continued innovations in the future.

Climate change presents another challenge for agricultural productivity, with studies documenting impacts on corn yields [47]. Adaptation to climate change is a rising concern [48, 49]. Some regions will gain and some will lose productivity as climate patterns evolve and crop production shifts among regions. US farmers generally see agricultural adaptation to climate change as a private problem. They expect to respond with managerial changes, such as adjusting crops, using irrigation, modifying leases and using crop insurance, while seed companies will breed varieties and hybrids adapted to new climates [50, 51]. Breeding will certainly be important for corn, since hybrids must be adapted to new photoperiods when changing latitudes. Also, seed companies have commercialized drought-resistant corn hybrids, but these and other traits providing yield gains under extreme conditions tend to be quantitative or polygenic and can imply productivity tradeoffs [52–54].

[6]Official US EPA news release: https://www.epa.gov/newsreleases/epa-registers-innovative-tool-control-corn-rootworm.

Despite these and other emerging challenges, several promising opportunities exist to continue the productivity gains for corn and agriculture more broadly, among them microbial seed treatments and gene editing techniques. Seed treatments have been used in crop production for some time, fungicides to protect seeds during storage, so that in the US all corn seed (both GE and conventional) uses fungicide seed treatments. More recently, insecticidal seed treatments became widely used in corn production, particularly neonicotinoid seed treatments, to control below-ground and early season insect pests. In the US, more than 90% of corn planted area uses neonicotinoid seed treatment [17, 55]. In addition to insecticidal properties, neonicotinoids have demonstrated plant grower regulator effects in the laboratory and are associated with increased early season vigor in the field [56].

These chemical seed treatments have contributed to observed corn yield productivity, but significant research focus has moved to microbial seed treatments, soil microbes and fungi that increase yields. These seed treatments improve the rhizosphere around crop seedlings and plants through a variety of mechanisms, such as increasing nutrient availability, controlling diseases or nematodes, or supplying plant growth hormones [57]. Though some microbial seed treatments have been commercialized, including for corn, research needs still exist before widespread commercialization and achievement of their potential can occur [58]. An interesting possibility is to engineer microbes or fungi to enhance soil microbes for agricultural use.

A variety of gene editing techniques have recently been developed (e.g., CRISPR/Cas9, TALENs, ZFNs) with agricultural applications only beginning to be realized. The cost of using gene editing techniques is relatively low compared to gene-transfer technology. Also, gene editing is likely to face lower regulatory burden, as it does not require gene transfer across species. Public acceptance exists for therapeutic human health applications and some agricultural applications as well [59, 60]. Applications to crops could include pest and pathogen control, as well as improved tolerance to abiotic stresses such as extreme heat or cold and drought, helping crop production adapt to climate change and increases in extreme weather events. Furthermore, gene editing could include the possibility of increasing the efficiency of photosynthesis in crops. Besides applications to crops directly, gene editing could be applied to other key organisms, such as to engineer soil microbes to develop new or more effective microbial seed treatments. Similarly, gene editing can be used to engineer gene drives in order to introgress select genes into populations in order to suppress or eliminate pest populations or to make herbicide-resistant weed populations susceptible to herbicides [61, 62]. Given the economic importance of corn and its existing research and commercial infrastructure, corn seems likely to be at the frontier of the next wave of such innovations in agriculture.

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