

# Long-Run Uncertainties for U.S. Agriculture

*By Rosamond L. Naylor*

In 2019, crop and livestock producers throughout the United States confront multiple challenges: trade restrictions, extreme weather events, late planting, low and variable commodity prices, and deteriorating infrastructure. Many conversations in rural America are focused on near-term profits, labor availability, land rental rates, and loan repayments for agricultural machinery. The immediate economic concerns of farm households form the basis for wide-ranging policy discussions at local to national levels.

Virtually all U.S. farmers also face economic and environmental uncertainties over the long term. These long-run uncertainties arise in a globalized food system, where trade policy and linkages between food, feed, and fuel markets work either to stabilize or destabilize commodity markets. Climate change and climate variability—extending beyond just “a year or two of bad weather”—add to the long-run unpredictability of the farm economy.

This paper focuses on three important categories of long-run uncertainty for U.S. agriculture: transitions in global food and fuel demand, the effects of a changing climate, and regional depletion of groundwater resources for irrigation. The definition of “long run” is confined here to a generation in time (approximately 30 years), although the same

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uncertainties would apply throughout the twenty-first century. While a full analysis of each category is beyond the scope of this paper, each section highlights some key areas of uncertainty, reviews recent evidence, and provides relevant examples.

Attention to long-term uncertainties in agriculture is important because farm households manage large amounts of expensive fixed capital, such as land, irrigation equipment, and farm machinery, which places a premium on long-range planning. In addition, understanding long-term uncertainties in agriculture, particularly as applied to climate adaptation and water resource management, is key for creating appropriate policy incentives for farmers through the U.S. Farm Bill and other state-level measures.

## **I. The Changing Nature of Demand**

The future trajectory of global agricultural demand typically provides an overall sense of optimism for U.S. farmers. The world's population is projected to grow by 30 percent over the next 30 years, from 7.6 billion in 2018 to roughly 9.9 billion by 2050.<sup>1</sup> Virtually all of this growth will occur in developing and emerging economies, where per capita incomes are also on the rise. Over the same period, the share of the world's population living in urban areas is expected to jump from 55 percent to 68 percent. These factors, set in the context of a globalized economy, will sustain growth in consumption of wheat- and maize-based products, animal protein, and a wide range of vegetables, fruits, nuts, and other commodities that comprise diversified diets.<sup>2</sup> As one of the world's largest producers and exporters of corn (maize), soybeans, wheat, commercial feeds, and meat products, the United States will likely benefit from these trends in global demand. Economic development in the Global South (a term used by the World Bank to refer to countries in Asia, Africa, Latin America, and the Caribbean considered to have low or middle income compared with the Global North) will also lead to increased demand for transportation fuels, including ethanol and biodiesel.

Despite the promise of anticipated growth in global food, feed, and fuel demand for the U.S. agricultural economy, there are three important areas of uncertainty surrounding future consumption patterns that merit careful consideration. The first involves the regional trajectory

of population growth and its implications for global agricultural markets, with a specific focus on Africa. The second encompasses potential shifts in consumer preferences toward nutritious and sustainable foods in both industrialized and developing economies. Finally, the future of the global biofuels market, which has relied to date on a combination of government subsidies, regulations, and targets in all major biofuel-producing countries, remains a large source of uncertainty for the global agricultural economy.

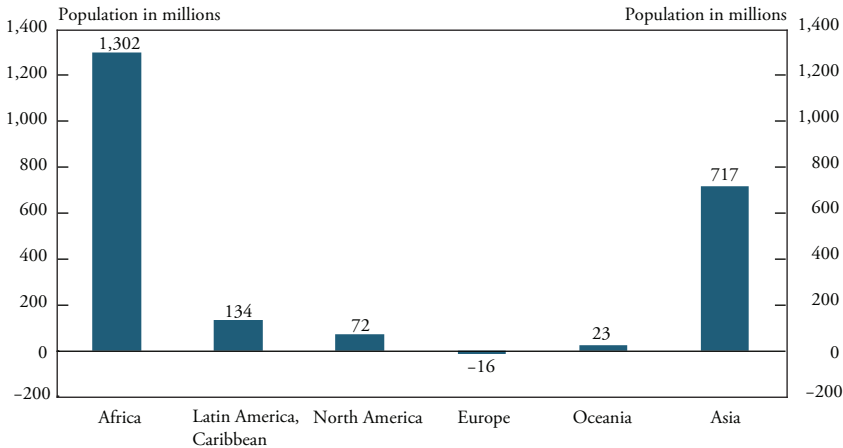
### *Africa's agricultural demand*

Africa's population is expected to double over the next generation, from 1.3 billion in 2018 to 2.6 billion in 2050, accounting for 58 percent of the global population increase by midcentury (Chart 1). To put this number in perspective, Africa will add 40 percent more people by 2050 than the rest of the world combined. Meanwhile, urbanization on the continent is projected to rise from 40 percent today to almost 60 percent by midcentury. China's population, by contrast, will decline by an estimated 50 million by 2050.

On a global scale, the total fertility rate (TFR) has been falling for decades and now stands at 2.4, less than half the rate of 4.9 recorded in the late 1960s and verging on the replacement level of fertility of about 2.1.<sup>3</sup> Yet throughout the African continent, fertility rates remain well above replacement rates in many countries, failing to follow the rapid pattern of demographic transition experienced in Asia and Latin America at similar stages of economic development.<sup>4</sup> Currently, 17 countries in the world have TFRs above 5, all of which are in sub-Saharan Africa. Niger, with the highest TFR at 7.2, is among the world's poorest countries. Nigeria, a country with greater economic potential, has a TFR of 5.5 and will replace the United States as the third most populous nation by 2050.

What these demographic trends imply for future consumption and trade in cereals, oil crops, animal feeds, and animal products is difficult to predict. Will wheat farmers in Kansas benefit from increased demand for bread and other processed wheat products as African cities expand? Will Louisiana farmers gain from continued growth in per capita consumption of rice in Africa? Will Iowa corn and soybean farmers find new export markets for feeds, meat products, and vegetable oils? Much

*Chart 1*  
Population Change by Major Region, 2018–50



Source: Population Reference Bureau.

of the uncertainty centers on the future trajectory of economic growth for the continent's 54 individual countries. For the past five years, from 2013–18, 30 percent of Africa's economies achieved an average annual rate of real GDP growth at or above 5 percent, but another 30 percent remained economically stagnant (World Bank Group 2019).<sup>5</sup> Large income disparities in many African countries—even in the fastest growing economies—make forecasts of future agricultural demand even more unreliable. In addition, Africa's bulging youth population, estimated to grow by 50 percent by 2050, will generate a precarious balance of youth unemployment and economic growth triggered by innovation and entrepreneurship throughout the continent, depending on each government's economic policies and investments in education and health.<sup>6</sup> For those economies that cannot adequately absorb their expanding youth populations, the risks of civil conflict loom large (Naylor 2018).

Even if Africa's economic trajectory could be predicted with a high degree of certainty, the implications for food, feed, and fuel consumption and trade remain unclear. Which types of animal protein will be most highly demanded in African countries as incomes rise—beef, pork, poultry, fish, eggs, dairy products? Will feeds be sourced internationally or produced and exchanged increasingly within the

continent? To what extent will growth in Africa's transportation fleets rely on regionally versus internationally produced biofuels?

Given the potential scale of Africa's agricultural demand over the next generation, answers to these questions are important for the U.S. agricultural economy. If Africa is, indeed, seen as a target of market opportunity for American farmers, the United States will need to adjust its long-term trade strategy promptly. A decade ago, the United States was one of Africa's main trade partners, along with Europe, Japan, and Brazil. Today, China and India have overtaken the United States and these other countries as Africa's main trading partners and infrastructure investors (*Economist* 2019). Historically, the United States has demonstrated a relatively weak commitment to many African countries due to a myriad of governance and geopolitical concerns; building long-term economic and trade relationships with leading African countries, such as Nigeria, Kenya, and South Africa, will be important for America's agricultural exports going forward.

#### *Food security, health, and the environment*

The second area of long-run uncertainty in global agricultural markets pertains to the future trajectory of human nutrition and consumer preferences. Although continued population growth implies "more mouths to feed," the demand for cereals and other starchy staples to meet basic calorie needs is well past its peak (Pingali 2015). The prevailing view that significant growth in staple grain supplies is needed to feed a world that will remain deficient in calories in 2050 is largely misleading. Most low-income households around the world—with the notable exception of those in protracted conflict areas—now have sufficient calories for an active working life in most years (FAO 2017; Naylor 2018). Extreme weather events, natural disasters, droughts, and political upheavals still result in regional food shortages and famines from time to time, especially in parts of sub-Saharan Africa (Devereux 2009; FAO 2018a; FAO and ECA 2018). The level of staple crop demand for direct food consumption has thus leveled off on trend, but the variation in demand persists due to factors largely outside the control of the communities in need. Meanwhile, a rising share of staple grains is being directed toward animal feeds, biofuels, and other industrial demands.

As basic calorie requirements are met for most populations around the world, the focus on global food security is being supplanted by a focus on global nutrition security. Many individuals living in poverty, and even those in low-to-middle-income groups, remain deficient in protein, micronutrients, and essential vitamins—a condition widely referred to as “hidden hunger” (Leathers and Foster 2017). Infants experiencing serious micronutrient and vitamin deficiencies during the first two years of life (including the gestation period in the womb) often suffer from stunting, contributing to permanent physical and cognitive impairments. There are other problems associated with hidden hunger as well: for example, iron deficiency causes anemia, leading to low labor productivity and poor achievement in school, and vitamin A deficiency causes night blindness and poor lung and gut function, particularly in children. Over two billion people worldwide currently suffer from some form of hidden hunger (Gödecke and others 2018).

Global malnutrition is also characterized by excess consumption. Diets rich in carbohydrates, sugar, and saturated fats contribute to serious health problems related to obesity, diabetes, and heart disease in both developing and industrialized countries. Middle-income countries are currently experiencing the most rapid growth in adult and childhood obesity as access to processed foods expands and daily physical activity declines (Leathers and Foster 2017). The global health implications of these trends are staggering, as the majority of the world’s population now lives in countries where overweight and obesity-related deaths exceed hunger-related deaths (WHO 2018). With mounting health costs at local to national scales, increased awareness of the links between dietary choices and health outcomes is likely to temper long-term growth in demand for cereals, oil crops, sugar, and meat on a per capita basis. Significant shifts in food preferences, should they occur in the future, would directly affect the U.S. agricultural economy.

Dietary choices are being discussed not only in terms of nutrition, but also in terms of their environmental consequences, particularly among scientific and advocacy groups in Europe and the United States. These discussions present an additional area of uncertainty for future agricultural demand. In January 2019, a report published by the EAT-*Lancet* Commission on “Food in the Anthropocene: Healthy Diets from Sustainable Food Systems” garnered considerable attention within international food and agriculture circles.<sup>7</sup> The report

advocated a rethinking of global food systems and food choices in alignment with the United Nations Sustainable Development Goals and the 2016 Paris Agreement on climate change mitigation. Building on a large and growing body of scientific studies, the report urged a significant shift in consumption and production toward plant-based foods and away from animal-based products, with specific recommendations tailored to countries according to their development and nutritional status. The EAT-*Lancet* report is just one of dozens of recent reports published by international organizations, non-governmental organizations, and scholars during the past decade that raise concerns about the unhealthy, unsustainable, and inequitable dimensions of the global food system.<sup>8</sup> The extent to which sustainability objectives will shape the future of global food systems over the coming decades remains unclear. What is clear, however, is that the international discourse and scientific focus on the health, environment, and equity aspects of food is intensifying.

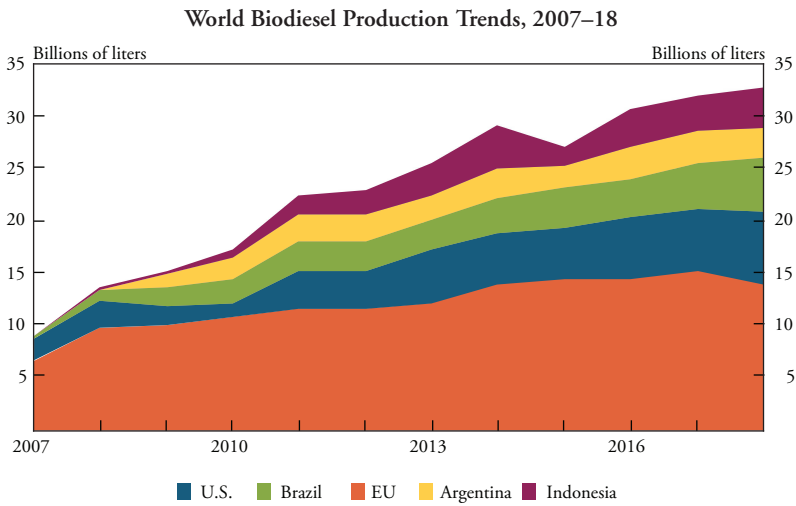
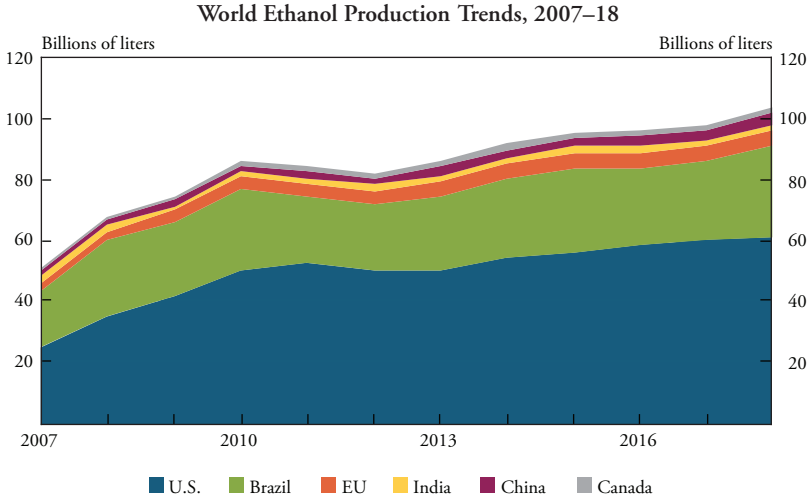
### *The long-term future of biofuels*

The future trajectory of ethanol, biodiesel, and advanced liquid biofuels presents a third layer of uncertainty for agricultural markets. During the past decade, global ethanol production more than doubled and biodiesel production almost quadrupled (Chart 2). The industry is concentrated geographically, with over 80 percent of global biofuels production and use occurring in the United States, Brazil, and the European Union in 2017 (REN21 2018). The United States has emerged as the world's largest producer of both ethanol and biodiesel, followed by Brazil and more distantly by Germany, Argentina, China, and Indonesia. Ethanol accounts for nearly three-quarters of liquid biofuel production today, but the balance is expected to tip increasingly toward biodiesel as diesel gains market share over gasoline in transportation fuels, particularly in developing countries where commercial truck fleets are expanding rapidly (Naylor and Higgins 2017).<sup>9</sup>

In 2017, the transportation sector accounted for almost one-third of final energy consumption worldwide, but only 3.1 percent of energy used in transportation was from renewable sources (REN21 2018). Biofuels accounted for 90 percent of the renewable portion (2.8 percent of total transportation energy), with electric vehicles constituting the

Chart 2

Growth in Global Production of Ethanol and Biodiesel among Major Producers, 2007–18



Source: Naylor and Higgins (2017) and REN21 (2018).



remainder. Looking ahead, rising incomes throughout much of the Global South over the next 30 years are expected to lead to rapid expansion in all forms of transportation—motorcycles, cars, buses, trucks, planes, boats, and rail. Whether or not biofuels will gain market share within this growing transportation sector will depend on government policies, corporate behavior, and consumer preferences related to energy security, sustainability goals, and relative prices of fossil fuels to biofuels. Crude oil prices have been highly variable during the past 15 years—varying by a factor of four, from roughly \$30 to \$120 a barrel in real terms—indicating that forecasts of fuel prices out to 2050 have a high degree of error.<sup>10</sup> The future of biofuels is also contingent on technological advances in areas such as cellulosic biofuels and aviation biofuels, which have been relatively slow to develop to date (REN21 2018).

The largest area of uncertainty in long-term biofuel projections is the future role of government policies, both within the United States and in other biofuel-producing countries. U.S. dominance in the global ethanol and biodiesel markets has resulted mainly from the establishment of mandates and other regulations and incentives for biofuel production and use within the federal Renewable Fuel Standard (RFS) legislation (EPA 2019; Naylor and Falcon 2011; Naylor and Higgins 2017). Roughly 40 percent of the U.S. corn crop now goes into ethanol, and with recent low commodity prices and continued trade battles with China, President Trump signed a new executive order in June 2019 to lift the summer season ban on fuels containing higher blends of ethanol (USDA ERS 2019). This ruling will permit an increase from E10 blends (10 percent ethanol and 90 percent petroleum, as currently mandated in the RFS) to E15 blends; the higher blends had been restricted for summertime use due to concerns of increased smog during periods of high temperatures. The United States also provides incentives for biodiesel through tax exemptions and restrictive trade policies, including anti-dumping duties on biodiesel imports from Argentina and Indonesia and a history of complex trade rules with the European Union (Naylor and Higgins 2017). Overall, the direction of U.S. biofuel policies continues to be a moving target, hinging largely on market conditions for corn and soybeans.

The scope of policy interventions on biofuels is global and massive in scale. More than 40 countries had mandates and other regulatory

Table 1

### Biofuel Mandates (Ethanol and Biodiesel) for the World's Major Producing Countries

Country	Ethanol mandate	Biodiesel mandate
U.S.	15 billion gallons in 2019	2.1 billion gallons in 2019
EU	B20 in overall energy mix by 2020; B10 in transportation sector; a maximum of 7 percent from food-based biofuels	
Brazil	E27 in 2018	B10 in 2018
India	E20 by 2030	B5 by 2030
China	E10 by 2020	None
Canada	E5; higher in some provinces	B2; higher in some provinces
Indonesia	E20 by 2025; currently no import or production of fuel-grade ethanol in Indonesia	B30
Argentina	E12 in 2018	B10 in 2018

Sources: U.S. Department of Agriculture (USDA), European Commission, U.S. Environmental Protection Agency, and the International Energy Agency. Adapted from Naylor and Higgins (2017).

policies supporting biofuel production and use in 2017 (REN21 2018). Table 1 shows the mandates for the world's major biofuel-producing countries. In most of these countries, including China, Brazil, and Indonesia, biofuel mandates have been aimed at boosting the demand for domestic agricultural feedstocks and promoting a transition from fossil fuels to renewable energy in transportation. In other countries, such as Norway and European Union nations, concerns over the sustainability and climate consequences of feedstock production have weakened biofuel incentives. The complex interactions among policies on energy, agriculture, trade, environment, and climate throughout the world make the future of crop-based biofuels highly unpredictable.

A final area of long-run uncertainty for the biofuels sector is the role of electric vehicles (EVs) in global transportation fleets. Globally, the number of EV sales has increased to record levels each year—albeit from a low base—and car manufacturers continue to roll out new electric vehicle product lines (REN21 2018). Sales of electric cars increased by 58 percent in 2016 alone, accounting for 1.3 percent of total passenger vehicles on the road (IEA 2018). North America is now the third largest market for EVs after Europe and China (REN21 2018).

Although EVs represent a small share of global transportation today, growth in this sector is fueled by policies and initiatives to advance the renewable energy sector. In 2017, five countries announced plans

to ban diesel and petroleum vehicles completely in the coming decades: India, the Netherlands, and Slovenia by 2030, and France and the United Kingdom by 2040. Also in 2017, the Global Electric Vehicles Initiative (EV30@30) was launched, setting a target for 30 percent market share of EVs among passenger cars, light commercial vehicles, buses and trucks by 2030 (IEA 2019). This initiative is backed by a growing list of countries, including Canada, China, Finland, France, India, Japan, Mexico, the Netherlands, Norway, Sweden, and the United Kingdom. Meanwhile, a coalition of corporations from China, Europe, and the United States, assembled by the Climate Group, introduced an “EV100” program to help accelerate a full replacement of petrol and diesel fleets with EVs, including the development of renewable electric charging infrastructure (Climate Group 2017).

The fact that the world’s two largest emerging economies—China and India—are among the many countries actively pursuing a transformation from petroleum- and diesel-powered transportation to EVs suggests that the future path of global biofuels cannot be assured. Even in the United States, sustainability concerns focused mainly on climate change have sparked a growing debate on the life-cycle environmental consequences of electric versus biofuel-based transportation, with supporters of EVs and biofuels pitted against each other (Martin 2017b).<sup>11</sup> How these trends and debates over energy, climate, and the environment will affect American farmers over the next few decades remains to be seen.

Ultimately, the 30-year trajectory of global agricultural demand for food, feed, and fuel is ripe with uncertainty. The long-run challenge of ensuring robust demand for staple agricultural products in the United States may even rival the widely declared challenge of producing enough food to feed a global population of 10 billion by 2050. What is clear, however, is that challenges on both sides of the agricultural demand-supply equation will be important for farming communities as they plan for the future.

## II. Climate Change and Variability

One of the largest uncertainties for agricultural supplies over the course of the twenty-first century centers on climate change and variability. The best way to think about climate is that it represents the

statistics of weather over time and space, and all farming communities have an eye on the weather. The effects of extreme weather events and natural disasters—heavy rains and floods, unseasonal hailstorms and blizzards, droughts, tornados, hurricanes, and severe heat waves—are experienced regularly by farmers throughout the world today. How the frequency, intensity, and location of such extreme weather events and natural disasters are likely to change in the future with rising mean global temperatures remains uncertain (IPCC 2014).

Climate change, or global warming, is a topic of widespread debate in U.S. society, but one need only look at the actions of the \$5 trillion global insurance industry to understand that climate change poses a substantial and increasing risk. In a 2018 survey of the global insurance industry, climate change was ranked for the first time as the leading current risk, emerging risk, and risk combination for 2019, rising above the perceived risks associated with cyber and infrastructure collapse, financial volatility, and price asset collapse (Rudolph 2019). Also in 2018, a survey by the Geneva Association, a major international insurance think tank, found that two-thirds of the companies within their sample have already integrated climate change into their business models, incorporating the full suite of physical, liability, and transaction risks (Golnaraghi 2018).<sup>12</sup> The elevated rank of climate change as a leading insurance risk reflects the rising frequency of extreme weather events and the increasing exposure of people and property to such events worldwide.

Regardless of how farmers in the United States articulate their views on climate change, most are in favor of crop insurance programs through the Farm Bill. A recent report by the Congressional Research Service (2018) shows that the federal crop insurance title of the Farm Bill had the second largest outlays after nutrition programs during the 2007–16 period, a pattern that is expected to persist through 2027.<sup>13</sup> In the 2014 Farm Bill, the federal crop insurance program became agriculture's largest producer support program, providing over \$100 billion of insurance protection annually for over 100 crops. Corn, soy, and wheat accounted for roughly 70 percent of enrolled acres and claim payments, with enrollment concentrated in revenue-based policies (which insure against a combination of production losses from natural causes and declines in commodity prices), followed by yield-based policies (which insure specifically against production losses from natural causes, such

as drought, floods, hail, wind, insects, and disease). Although federal subsidies on insurance premiums differ by level of coverage and type of program, the Federal Crop Insurance Corporation paid 61 percent of the premiums in aggregate from 2007 to 2016, while producers paid 39 percent.

### *Precipitation and extreme events*

When asked about future climate uncertainties, farming communities generally talk about rainfall and extreme events, such as floods, droughts, tornados, and hurricanes. Such events have widespread effects on their livelihoods, properties, and personal lives through injury and death. Since the start of 2019, eight Corn Belt states along the Mississippi have experienced record, long-lasting rainfall—more than 2 feet of precipitation in the lower regions and up to 40 inches in some areas—causing historic delays in planting or no planting at all (National Weather Service 2019a; see also Good 2019). In the five months between January and May 2019, the National Weather Service also reported an all-time record of over 1,000 tornados throughout the United States, over half occurring in May alone (National Weather Service 2019b).

The frequency and intensity of heavy precipitation events across the United States have increased more than average precipitation during the past 50 years, a trend that will likely continue well into the twenty-first century (National Climate Assessment 2018).<sup>14</sup> At the same time, surface soil moisture over most of the United States is expected to decrease with greater temperatures over the coming decades, raising the specter of worsening drought conditions in some regions, particularly in the Southwest and Southern Great Plains. As important as these conditions are for the U.S. agricultural sector, long-range predictions of the timing, location, and intensity of extreme weather events cannot be made with much confidence (IPCC 2014).

A related source of uncertainty for farmers over the next 30 years will be the cost of crop insurance premiums and the extent of federal insurance subsidies as the effects of climate change unfold. Between 1980 and 2018, the United States experienced an average of 6.3 extreme weather events per year with damages over \$1 billion each (inflation-adjusted); during the most recent five years (2014–19), the number doubled to 12.6 extreme events per year.<sup>15</sup> With the rising number of

extreme weather events per year in the United States, it is highly likely that crop insurance premiums will also increase.

### *Yield outcomes from rising temperatures*

Although farming communities generally focus on risks related to precipitation, climate experts tend to focus on future warming trends for several reasons. First, both the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) have reported rising global temperatures since the turn of the twenty-first century, and the past five years alone have been the warmest since modern recordkeeping began (NOAA 2019; NASA 2019). In addition, the projected increase in mean temperatures around the world is large relative to historical variability, and there is much greater agreement in the global climate models on future temperature versus precipitation forecasts (Lobell and Burke 2008; Battisti and Naylor 2009; IPCC 2014). In all but the most aggressive scenario for greenhouse gas emission reductions—a highly unlikely scenario given that carbon dioxide emissions continue to rise—the global annual mean temperature is expected to increase by 2 degrees Celsius by midcentury compared with the 1980–99 average (IPCC 2014).<sup>16</sup> Numerous studies have concluded that warming of this magnitude will lead to substantial declines in average crop yields, and that the most serious agricultural consequences will occur in the tropics (Battisti and Naylor 2009; Porter and others 2014; Asseng and others 2014; Zhao and others 2017). For every degree Celsius increase in the global mean temperature, holding all else constant, yields are projected to decrease on average by 7.4 percent for corn, 6 percent for wheat, 3.2 percent for rice, and 3.1 percent for soybeans (Zhao and others 2017).<sup>17</sup>

The effect of extreme temperatures on crop yields depends on the timing of heat or freezing events. High temperatures negatively affect plant development in multiple ways and at different times in the growing season, such as through reduced spikelet fertility, reduced grain filling, and increased respiration (Porter and others 2014; Sánchez, Rasmussen, and Porter 2014). Freezing temperatures can push plants toward dormancy by shutting down tiller formation. In a study that measured wheat yields in Kansas varietal trials against location-specific weather data from 1985–2013, Tack and others (2015) showed that

the largest effects of temperature-induced yield loss were due to freezing temperatures in the fall and extreme heat events in the spring.<sup>18</sup> The net effects of warming were uniformly negative across wheat varieties, even when accounting for lower exposure to freezing. The study highlighted an important trade-off in crop breeding: many new varieties in the field trials have relatively long grain-filling stages to increase yield potential under ideal conditions, but this long grain-filling period makes the plants more vulnerable to heat stress in high temperature seasons. Spring rainfall can ease heat stress in wheat and other crops, and additional irrigation can be used as an adaptation strategy to reduce the effect of high temperatures on yields during the long grain-filling stage. However, the availability of water for irrigation poses additional uncertainties for farmers in the future.

### *Climate effects on crop pests and pathogens*

While many studies of climate effects on agriculture focus on the direct relationships between temperature, precipitation, and crop yields, the indirect effects of climate change on the evolution and spread of pest and pathogens in agriculture may be more serious—and significantly less predictable. Plant species differ in their defense mechanisms to biotic stress under changing climate conditions. These differences are not directional—that is, some crop species demonstrate stronger defense strategies, while others become more susceptible to pests and pathogens under varying climate conditions—and it is difficult to aggregate the varying response mechanisms at regional or global scales. Elevated carbon dioxide can also shift a given plant's natural defenses to favor some types of crop diseases over others (Zhou and others 2019). Climate change affects more than a crop's defense behavior to pests and pathogens; it also affects the evolution and movement of pests and pathogens themselves (Velásquez and others 2018). Overall, the interactions between crops, pests, and pathogens in the context of climate change are highly complex and poorly understood (Gregory and others 2009).

Farmers in temperate regions are likely to be affected by crop pests and pathogens that respond to warmer winters and shorter (or nonexistent) freezing fallow seasons. Wetter and milder winters will increase the survival of certain winter annual weeds, and longer growing seasons will allow summer annual weeds to move northward—patterns that are

already evident in parts of Europe and North America (Peters and others 2014). Warmer and more humid growing conditions with year-round cropping will also facilitate the spread of fungal diseases, such as leaf rust for wheat. A recent study by Caubel and others (2017) showed that with milder winters in France, wheat rust establishes earlier in the season, augmenting fungal infections and sporulation efficiencies and leading to more virulent leaf rust cycles.

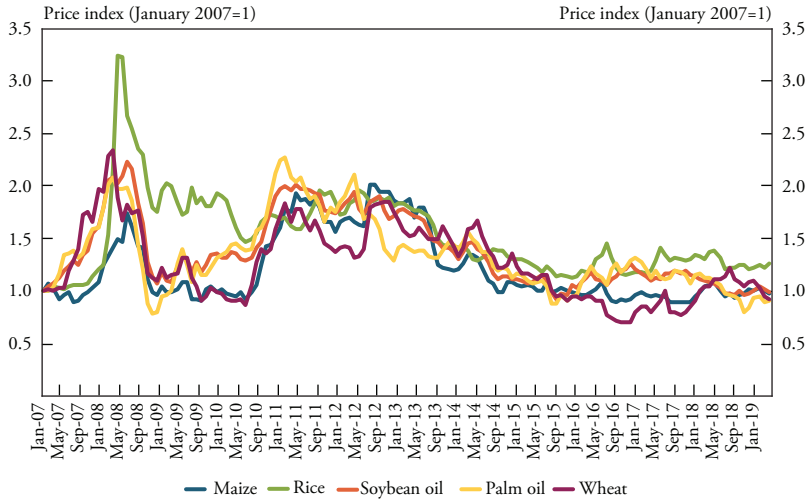
Warmer climates will also increase the metabolic rate of insect pests and allow insects to expand their range into higher latitudes, thus potentially exacerbating plant herbivory as well as the spread of insect-transmitted viruses, bacteria, and fungi. Deutsch and others (2018) modeled these insect dynamics for rice, wheat, and corn on a global scale and projected increases in yield losses of 10–25 percent per degree Celsius of global warming associated with climate-induced pest pressure from range expansion and herbivory, with the highest losses in temperate areas. In tropical areas, the increase in insect pest metabolism is somewhat offset by a decline in growth rate and expansion, as insects in these regions already operate near their optimum temperature range. Scientists at the Universities of Exeter and Oxford have recorded the movement of crop pests toward the North or South Poles since 1960 and have measured a rate of 2 miles (3 kilometers) per year on average for all pests and a northward movement of 12 miles per year for insect pests in particular.<sup>19</sup> Still, there is much to be learned about the dynamics of insect infestations in temperate agricultural systems, particularly regarding predator behavior and natural plant defense mechanisms.

A key question for the next 30 years is whether or not breeding efforts can stay ahead of both direct (abiotic) effects of climate on crop yields due to heat stress, droughts, and excessive rainfall and indirect (biotic) stresses from pests and pathogens. Management strategies for abiotic stresses, such as early planting or increased irrigation, may not be effective at curtailing biotic stresses from pests and disease. Even with new forms of chemical and genetic controls, it is highly possible that crop production in the United States and other temperate zones will become more variable with the spread of overwintering pests and diseases.



Chart 3

### Variability in Agricultural Commodity Prices, January 2007– April 2019



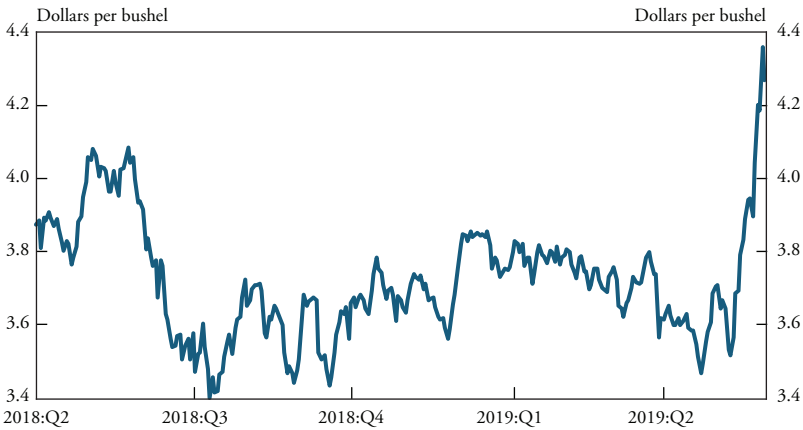
Notes: Prices are nominal. Maize: U.S. No.2 Yellow, FOB Gulf of Mexico, U.S. price, US\$ per metric ton; wheat: No.1 Hard Red Winter, ordinary protein, Kansas City, US\$ per metric ton; rice: 5 percent broken milled white rice, Thailand nominal price quote, US\$ per metric ton; soybean oil: Chicago Soybean Oil Futures (first contract forward) exchange approved grades, US\$ per metric ton; palm oil: Malaysia Palm Oil Futures (first contract forward) 4–5 percent FFA, US\$ per metric ton.

Source: International Monetary Fund.

### *Climate effects on market volatility*

Yield variability is a key concern for farmers throughout the United States as it affects farm revenue streams, crop insurance premiums, and in some cases, overall market volatility. International grain and oil crop markets have been highly volatile for over a decade, with peak monthly prices exceeding low monthly prices (in nominal terms) by 200 percent to 300 percent from 2007 to 2019 (Chart 3).

Several factors are contributing to this pattern of volatility, including international financial fluctuations and trade, biofuel, and stocking policies, but climate-induced production shocks also play an important role. As a recent example, record delays in corn planting in the U.S. Midwest due to extreme wet weather caused the Chicago Board of Trade (CBOT) corn price to jump to a three-year high in late May 2019, reversing (at least temporarily) an extended period of low prices for farmers (Chart 4). Severe rainfall, floods, droughts, heat waves, and

*Chart 4***Spike in Corn Price in May 2019 with Extreme Wet Weather and Delayed Planting**

Note: Nominal price on vertical axis (CBOT, USD/bushel), time on horizontal axis (Feb. 2018–May 2019).  
Source: USDA National Agricultural Statistic Service.

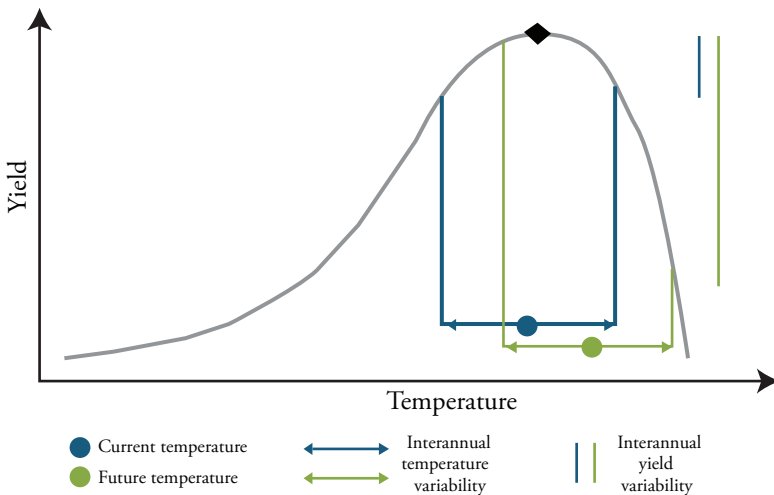
natural disasters that affect yields in the world's major breadbaskets often produce ripple effects throughout the world food economy.

In highly managed, high-yield cropping systems, such as those in North America, climate variability accounts for a relatively large share of the total yield variance compared with low-yield environments, where agronomic and management conditions have a greater influence. Empirical studies of climate change and agricultural yields in the United States indicate that major crops, such as corn, have an optimal temperature for performance, beyond which yield levels rapidly decline (Schlenker and Roberts 2009; Urban and others 2012). As illustrated in Figure 1, an increase in the mean temperature beyond the optimum growing temperature can also result in greater yield variability, even if interannual temperature variability remains the same.

Extreme crop losses in large producing countries are currently rare due to the highly controlled environment and technology under which these crops are grown. However, yield variability is expected to increase significantly under future warming conditions, unless heat-tolerant varieties or other adaptation measures, such as increased irrigation, are adopted. Modeling the potential effects of rising global temperatures on corn yields around the world, Tigchelaar and others (2018) find

Figure 1

## Schematic Representation of Temperature-Yield Relationship



Notes: In the absence of breeding for heat tolerance, an increase in mean temperature beyond the optimum temperature (black diamond) will lead to a decrease in mean yield and an increase in yield variability, assuming interannual temperature variability stays the same.

Source: Tigchelaar and others (2018).

that increased yield variability in the world's major producing countries is likely to lead to greater market volatility worldwide.<sup>20</sup> Their analysis shows that the probability of climate-induced yield losses greater than 10 percent for the top four corn-producing countries (United States, China, Brazil, and Argentina) is negligible today but rises dramatically with a 2 degree Celsius increase in growing season temperatures by mid-century (Table 2). The probability of significant yield losses jumps even higher as growing season temperatures rise by 4 degrees Celsius, an outcome that is not farfetched given current trends in global greenhouse gas emissions and carbon dioxide concentrations in the atmosphere (Global Carbon Project 2018).

Assuming that weather varies independently between geographic regions, the chance that maize production will fall by more than 10 percent in all four countries in the same year is zero today but rises to 6 percent under 2 degree Celsius warming and 86 percent under 4 degree Celsius warming. Similar results hold for the world's four largest exporting countries (United States, Brazil, Argentina, and Ukraine). Given that the top four producing countries comprise more than two-thirds

Table 2

### Percent Probability of Climate-Induced Yield Losses for Corn-Producing Countries

Country	Present day		2°C warming		4°C warming	
	>10 percent	>20 percent	>10 percent	>20 percent	>10 percent	>20 percent
United States	3.8	0.0	68.6	29.5	100.0	96.9
China	6.6	0.0	46.2	16.8	98.8	89.2
Brazil	1.4	0.0	38.7	9.4	90.5	64.1
Argentina	3.4	0.1	50.0	9.9	96.9	86.9
Ukraine	2.5	0.3	51.8	19.2	98.2	85.0
Top four producing (United States, China, Brazil, Argentina)	0.0	0.0	6.1	0.0	86.6	48.1
Top four exporting (United States, Brazil, Argentina, Ukraine)	0.0	0.0	6.9	10.0	86.1	45.8

Note: Table shows probability that in any given year, the relative yield in a country's most productive region will decline by 10 percent or 20 percent of the present-day mean yield for the top corn-producing countries individually (top), and combinations of the countries that produce or trade the most corn (bottom).

Source: Tigchelaar and others (2018).

of global production—and the top four exporters contribute around 87 percent of global corn exports—this analysis portends substantial volatility in international corn markets over the long term in the absence of significant adaptation. More generally, widespread volatility in corn production has implications for global agricultural markets as a whole, as corn is often considered to be the lynchpin of the world food economy. Corn accounts for around one-third of global cereal production and trade, and it is closely linked to other cereal and oil crop markets through its versatile role in food, feed, and biofuel markets (Naylor and Falcon 2011).

In addition, it is highly likely that agricultural market volatility resulting from climate shocks will be amplified by intervening trade policies. Widespread evidence on the political-economy dynamics of food and agriculture shows that governments around the world tend to restrict cereal trade during times of international price volatility to stabilize domestic food and agricultural markets (Swinnen 2018; Battisti and Naylor 2009). During the 2006–08 food crisis, for example, large maize-exporting countries, such as Brazil, Argentina, and Ukraine, imposed export bans (thus lowering export supply in world markets), while importing countries introduced trade incentives to lower the price of imported grain (thus raising import demand) (Abbott 2012).

The result was a much larger international price shock for cereals than would have been the case had free trade prevailed (Naylor and Falcon 2010; Martin and Anderson 2012).

The upshot is that climate effects on agricultural productivity—combined with government restrictions on trade to stabilize domestic markets—are likely to have multiplier effects on agricultural prices and farm incomes. Synchronous climate shocks among major grain-trading countries will exacerbate global market volatility. Given the current trend toward protectionist trade policies, climate-induced price volatility poses increasing uncertainty for farmers in both the short and long run.<sup>21</sup>

### III. Groundwater Depletion for Irrigation

An important adaptation option for farmers facing climate-induced yield volatility is to irrigate their crops with greater intensity in seasons of dangerously high heat and low rainfall. Irrigation increases crop evapotranspiration, allowing the land surface to remain cooler than it otherwise would be under heat- and water-stressed conditions. The main risk that this solution presents is excessive demand for freshwater resources and the depletion of groundwater in regions where extraction exceeds aquifer recharge.<sup>22</sup> Ongoing challenges of groundwater depletion in two of the world's major breadbaskets—the U.S. Ogallala Aquifer region and the Punjab region of India—are presented here to illustrate the potential enormity of the problem.

On a global basis, irrigation already accounts for around 70 percent of freshwater withdrawals and 90 percent of consumptive water use (Siebert and others 2010). With population growth and rising per capita incomes, global freshwater use has expanded six-fold over the past century, and is expected to rise by another 20–30 percent by 2050 (UNESCO 2019). The area currently equipped for irrigation worldwide exceeds 300 million hectares, of which an estimated 38 percent relies on groundwater (Siebert and others 2010).

#### *The Ogallala Aquifer*

The risk of groundwater depletion is on the minds of many U.S. farmers as they track the decline in water levels in the Ogallala (High Plains) Aquifer. The annual rate of groundwater extraction from the Ogallala Aquifer is eight to 10 times the rate of natural recharge in some

regions, threatening groundwater depletion over the next 30–50 years (National Climate Assessment 2018). Agriculture accounts for over 90 percent of the water pumped from the Ogallala. The aquifer supplies water for about one-third of all irrigated agriculture in the country, and roughly one-fifth of all wheat, corn, cotton, and cattle produced in the United States come from the High Plains region (Little 2009; Frankel 2018). The potential long-term consequences of depleting the aquifer include a decline in both the quantity and quality of groundwater. Although groundwater tends to be less polluted than surface water, levels of arsenic and other toxins can become concentrated and increasingly dangerous when aquifers recede.

Predicting future water levels in the Ogallala Aquifer is not a simple task. The aquifer spans eight states, each with its own policies and practices for groundwater extraction. Depending on how aggressively farmers throughout the High Plains extract groundwater, the Ogallala could be largely depleted by midcentury, or it could be sustained for well over 100 years (Parker 2016). The lack of coordinated management of surface water and groundwater within and among states limits the region’s ability to address potential climate effects on the agricultural sector (National Climate Assessment 2018). For example, the Nebraska state government has been relatively successful in enforcing reductions in groundwater extraction, while the neighboring state of Kansas has little, if any, legislative control over excessive pumping for irrigation, particularly in the western portion of the state (Frankel 2018). Reporting on the situation, Brown (2018) aptly concludes, “Kansas agriculture faces an existential choice: it can cut back water use voluntarily now and face a decline in farm productivity, or it can continue to ignore the problem and face far more dire consequences as the water runs out.” Several agricultural communities in Kansas have recently signed on to voluntary groundwater reduction programs and have begun to adopt soil and water conservation practices to sustain agricultural yields well into the future. Farmers’ immediate attention, however, appears to be focused more on earning a viable living in the short run so they can survive into the long run.

*Groundwater extraction in northwest India*

Agricultural communities in the United States will also be affected by groundwater depletion in other regions of the world, particularly those producing crops that compete with the U.S. in international markets. India is a prime example, given its role as the world's second-largest producer of both wheat and rice behind China. In 2018, India produced an estimated 99.7 million metric tons (mmt) of wheat (roughly double the U.S. production of 51 mmt), and 116 mmt of milled rice (about 16 times that of the United States) (FAO 2018b). India was also the world's largest rice exporter in 2018, accounting for 30 percent of global exports. Wheat is a major irrigated crop in India, as is rice in some Indian states. The country's production of both crops has expanded significantly since high-yielding cultivars were introduced in the late 1960s as part of the Green Revolution. Irrigation, fertilizers, and favorable economic incentives have been crucial to making the Green Revolution for wheat and rice so successful.

India's agricultural sector draws water from both surface and groundwater sources, but groundwater has become increasingly important over the past half century. (Groundwater and surface water are linked through conjunctive use; surface water, including leakage from canals, helps to recharge groundwater tables to varying degrees across India's hydrological landscape.) Research by Srivastava and others (2018) shows that the share of irrigation from groundwater has doubled from 30 percent in 1964-65 to 63 percent in 2014-15 for India overall, with variation among states in their extent of irrigated cropped area and groundwater dependency. In the drier, northwestern states of Punjab, Haryana, and Rajasthan, where wheat and rice are widely cultivated, the majority of irrigation comes from groundwater. Groundwater extraction exceeds replenishment in these three states and water tables are declining significantly.

India has become the largest user of groundwater in the world, exceeding the extraction rates of the United States and China combined (Siebert 2010). Agriculture accounts for 90 percent of the country's total groundwater use. More than 20 million wells of various depths provide water for irrigation, and as water tables have declined in some areas of the country, the share of deep tube wells has increased. The estimated number of deep tube wells used for agriculture has risen from

around 100,000 to 2.6 million over the past 30 years (Kishore 2018). The spread of deep tube wells is supported by substantial subsidies on rural electricity, especially in the northwestern states (Srivastava and others 2018).

The rate at which India's groundwater will be depleted in the future depends on climatic conditions controlling growing season temperatures, the South Asian monsoon, and the melting of Himalayan glaciers. Increased growing season temperatures and glacial melt can be predicted with a relatively high degree of certainty, whereas long-run patterns of monsoon onset, intensity, and area extent are much less certain (IPCC 2014). The monsoon supplies around 70 percent of the country's annual rainfall and is thus hugely important for Indian farmers. Parts of India are currently facing one of the worst droughts in history as a result of a delayed and weak monsoon season; the lack of water and extreme heat, approaching 50 degrees Celsius in some western states, has caused widespread deaths and farm abandonment. Meanwhile, India's sixth-largest city, Chennai, whose population now exceeds that of Los Angeles, has essentially run out of water. One need not look far to the future to measure the effects of monsoon variability on the Indian population.

Irrigation provides an important adaptation option for many farmers suffering the effects of low rainfall and extreme heat, at least in the near term, depending on their proximity to surface and groundwater resources. Glacial melt is higher in warmer years, helping to offset drought stress. However, increased glacial runoff from the Himalayas due to warming is expected to peak by 2050, reducing the protection that glacial melt will provide for farmers in India over the long term (Pritchard 2019). Overall, there is a substantial risk of unsustainable groundwater use throughout India by midcentury as a result of both irrigation expansion and climate change, even in areas that experience precipitation increases in the future (Zaveri and others 2016).

In India, the U.S. High Plains, and other irrigated regions where groundwater depletion poses a significant threat to society, the adoption of advanced technologies that improve irrigation efficiency provides a possible remedy. Given that water is essentially free for farmers throughout most of the world, however, they typically have little incentive to improve irrigation efficiency on their own. The solution has been for



governments to provide additional subsidies, which has often proven to be counterproductive; producers may save water at the farm scale but increase water use at the basin scale through area expansion (Grafton and others 2018). Over time, the beneficiaries of these subsidies often lobby for continued support, making the problem even worse. This process has occurred, for example, in India's western state of Rajasthan, where subsidies for drip irrigation have led to the expansion of irrigated area and increased water use in agriculture (Birkenholtz 2017). Without a carefully monitored and enforced cap on groundwater extraction at the basin scale, even the best intentions for water use efficiency may result in groundwater depletion.

For all irrigated agriculture, the role of government policy is paramount. Providing farmers with essentially "free" water and subsidized energy to pump water creates perverse production incentives and conditions for rent-seeking and corruption. In India, the world's largest democracy, rural votes can be won through farm subsidies. The difficulties that the United States has faced in pricing water at its true opportunity cost provide a useful warning of how challenging the task will be for India to align objectives for water resource conservation with incentives. India has the world's largest number of people living under the poverty line, and its need to improve rural incomes and food security in the short run often comes at the expense of sound groundwater management over the long run. How government policy will shape farmers' use of water resources over the next 30 years is daunting and highly uncertain with respect to poverty levels, hunger, rural health, and migration.

## Conclusion

This paper has highlighted three important areas of long-term uncertainty for U.S. farmers: the changing nature of agricultural demand, climate effects on crop production and market volatility, and the depletion of groundwater resources for irrigation locally and globally. In all three areas, government policy within large agricultural economies will play a critical role in shaping the economic and biophysical conditions under which farmers will operate. International market conditions for food and agriculture reflect the residual effects of national policies around the world, and it is virtually impossible to predict government policy for multiple countries over the long term.

Despite the difficulty of making future projections on the direction of government policies worldwide, some points of predictability are bound to challenge the next generation of farmers. For example, sufficient scientific evidence shows that global mean temperatures will increase by 2 degrees Celsius or more by midcentury unless draconian geo-engineering efforts are mobilized, which would only accentuate climate uncertainties for all nations in the long run (IPCC 2014; Barrett and others 2014).<sup>23</sup> In a warmer world, how will the location and composition of cropping systems change within individual countries over the next 30 years? Will groundwater resources become more or less stressed? Given current cropping systems, a 2 to 4 degree Celsius warming will have significant effects on crop yield levels and variability. In addition, major grain-producing countries are likely to face synchronous shocks in agricultural productivity that could lead to increased future volatility in world markets.

Experience during the past 15 years has also indicated that governments tend to protect domestic consumers and producers in the face of rising volatility, leading to even greater instability in global markets (Swinnen 2018). Food price volatility hurts poor consumers and urban consumers, but it also raises the level of uncertainty that farmers experience over the long term, which may affect agricultural investments worldwide. Even in countries such as the United States, where crop insurance programs are robust, farmers face uncertainty in insurance coverage and premiums over the long run.

At stake is the future of the rural economy, as well as the future of global food security. What is different about the challenges that farmers will face over the next 30 years, as opposed to their immediate concerns today, is the magnitude of variability and uncertainty that exists along multiple fronts. The risks of increased volatility in agricultural markets, changing demand patterns, and protectionist trade policies make rural communities within and outside of the United States particularly vulnerable to economic hardship. Perhaps the biggest unknown is whether, in the face of such expansive vulnerability, promising young farmers will choose to stay in agriculture over the next generation. If the best and brightest farmers move out of agriculture, global food security will surely be jeopardized.

## Endnotes

<sup>1</sup>Demographic data for this section of the paper are from the Population Reference Bureau (2018) and the United Nations World Population Prospects (2019).

<sup>2</sup>Economic principles indicate that the income elasticity of demand for food in the aggregate declines with income growth (Engel's Law), meaning the share of income spent on food in the aggregate declines as incomes rise. At a disaggregated level, Bennett's Law states that the share of calories derived from starchy staples declines as incomes rise, and that individuals diversify their diets into vegetables, fruits, nuts, animal products, and other foods with relatively high income elasticities (Timmer, Falcon, and Pearson 1983).

<sup>3</sup>The TFR is defined as average number of children born to women in the child-bearing cohort, assuming that all women live to the end of their childbearing age. The replacement level of fertility is the average number of children born per woman at which a population exactly replaces itself from one generation to the next (without migration); this rate is approximately 2.1 children per woman depending on mortality rates in any given country. These projections assume current mortality trends and the absence of a pandemic disease outbreak in Africa or other parts of the world.

<sup>4</sup>The demographic transition is defined by a shift from high birth rates and high death rates to low birth rates and low death rates over the course of economic development. The precise pattern differs by country, but death rates typically fall before birth rates, as lower infant mortality ensures a desired family size.

<sup>5</sup>Stagnant economies are defined in this paper as those with average real GDP growth per capita at or below zero for the 2013–18 period.

<sup>6</sup>Africa will have over 360 million young people between the ages of 15 and 24 years by 2050, ready to enter the labor force. For further information on Africa's increasing youth population, see Page (2014) and Sow (2018).

<sup>7</sup>EAT is an independent, nonprofit organization based in Oslo, Norway and founded by the Stordalen Foundation, Wellcome Trust, and the Stockholm Resilience Centre. The EAT-*Lancet* Commission convened 37 leading scientists from 16 countries in various disciplines including human health, agriculture, political sciences, and environmental sustainability to develop global scientific targets for healthy diets and sustainable food production. The report was translated into multiple languages for international access.

<sup>8</sup>For a list of such reports, contact Rosamond Naylor, the author of this paper.

<sup>9</sup>The share of diesel in transportation demand is expected to increase at various rates in all countries, and at a global scale, biodiesel is expected to account for 70 percent of renewable transport fuel demand growth by 2040 (Naylor and Higgins 2017). The biodiesel sector includes fuel from fatty acid methyl esters and from hydrotreated vegetable oil.

<sup>10</sup>One can examine either crude oil or diesel in relation to ethanol and biodiesel, as the correlation between crude and diesel prices was 0.98 between 2000 and 2017 (correlation is between the Europe Brent Spot Price FOB and the Los Angeles, CA Ultra-Low Sulfur CARB Diesel Spot Price).

<sup>11</sup>Scientific consensus indicates that both biofuel- and electric-powered vehicles have environmental advantages over conventional fossil fuel transportation; which of the two has a comparative economic and environmental edge depends on the source of energy for EVs and the feedstocks used in biofuels (Martin 2017a).

<sup>12</sup>The reinsurance industry is even more active in the climate change space; for example, Munich Reinsurance Company, the world's largest reinsurance company, has been addressing insurance-related risks and opportunities associated with climate change for several decades in its risk assessments, asset management strategies, and global partnerships and initiatives (Munich RE, n.d.; *Reinsurance News* 2019).

<sup>13</sup>The federal crop insurance program is permanently authorized and receives mandatory funding; as a result, it will continue to operate even if Congress fails to pass future Farm Bills (CRS 2018).

<sup>14</sup>Data on average and extreme precipitation over the past 50 years are compared with data over 100 years from 1901–2016.

<sup>15</sup>According to data from NOAA's National Centers for Environmental Information (2019), the United States has experienced 246 weather and climate disasters since 1980 where overall damages or costs reached or exceeded \$1 billion (including CPI adjustment to 2019). The total cost of these 246 events exceeds \$1.6 trillion.

<sup>16</sup>A report by the Global Carbon Project estimated an increase in carbon dioxide emissions of 2.7 percent in 2018, sharply up from the 1.6 percent rise in 2017, and from the plateau in 2014–16. With the exception of the European Union, almost all countries contributed to the rise in carbon emissions, with emissions in China rising by 4.7 percent, in the United States by 2.5 percent, and in India by 6.3 percent in 2018 (Global Carbon Project 2018). Carbon dioxide concentrations in the atmosphere reached a record level of 415 parts per million in May 2019 (Harvey 2019).

<sup>17</sup>Zhao and others (2017) measured the effect of temperature on yields of these four major crops using four different analytical methods: global grid-based models, local point-based models, statistical regressions, and field warming experiments. The study did not look at carbon dioxide fertilization; effective adaptation, such as irrigation or planting dates; or genetic improvements. The authors note that elevated atmospheric carbon dioxide can stimulate crop growth when nutrients are not limited, but it can also increase canopy temperature from more closed stomata. See Long and others (2006) for further evidence on the limited effects of carbon dioxide fertilization on yield growth.

<sup>18</sup>Tack and others (2015) use regressions to measure yields from trials of 268 wheat varieties in Kansas against daily minimum/maximum temperatures and total precipitation pertaining to the specific sites.

<sup>19</sup>The database consists of 612 species of pests and pathogens distributed worldwide. Most of the pests are insects, nematodes, bacteria, or viruses (Nature's Half Acre, n.d.).

<sup>20</sup>The model used by Tigchelaar and others (2018) assumes constant technology (for example, no improvement in heat tolerance due to breeding) and constant management, and thus abstracts from reality. The top four countries for maize production and exports were selected on the basis of average production and trade values over the period 2012–17.

<sup>21</sup>This paper does not focus explicitly on trade policy as a major theme of uncertainty, as international trade was the topic of the Federal Reserve Bank of Kansas City's Agricultural Symposium in 2018, "Agriculture in a Global Economy."

<sup>22</sup>This section of the paper is relatively brief, as it follows from the 2016 Agricultural Symposium hosted by the Federal Reserve Bank of Kansas City on "Agriculture's Water Economy."

<sup>23</sup>Carbon dioxide persists in the atmosphere for over a century; given the current carbon dioxide concentration of 415 parts per million, the atmosphere will continue to warm through midcentury regardless of any change in global carbon dioxide emissions. For more information, see IPCC (2014) and National Climate Assessment (2018).

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