Chapter Title: AGRICULTURE

Book Title: Economic Risks of Climate Change
Book Subtitle: An American Prospectus
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Published by: Columbia University Press . (2015)
Stable URL: http://www.jstor.org/stable/10.7312/hous17456.13

CHAPTER 6

AGRICULTURE

Agriculture has long been an economic and cultural foundation for the United States. Known for historical boom and bust cycles, agricultural productivity and incomes are often influenced by and in turn influence the U.S. economy as a whole (Landon-Lane, Rockoff, & Steckel 2011; Hornbeck & Keskin 2012; Feng, Oppenheimer, & Schlenker 2013). In agriculture-dependent regions, the extreme drought and environmental mismanagement of the Dust Bowl in the early 1930s exacerbated the already dire economic conditions of the Great Depression (Egan 2006; Hornbeck 2012). Climate and weather variability have played roles to varying degrees in the cycles of U.S. agriculture. Extremes in local and regional weather patterns and climate variability have disrupted agricultural production in the past. American farmers have developed production practices and strategies appropriate for their local conditions, taking into account long-term historical trends as well as the risks of short-term variability. Despite the flexibility of the U.S. agricultural system and advances in agricultural practices and technologies, U.S. production and prices remain highly dependent on climate, making the sector particularly vulnerable to both gradual climate change and extreme climate events.

The agricultural sector's central role in rural and local economies and the national economy, as well as its importance for human health and security, make understanding the economic risks posed by climate change important not only for agricultural states but also for farmer livelihoods, rural communities, and the U.S. economy as a whole. The United States produced more than $470 billion in agricultural commodities in 2012. Although agriculture has traditionally contributed less than 2 percent of U.S. GDP, it is a much more significant source of income for many Midwest and Great Plains states such as North Dakota, South Dakota, Nebraska, and Iowa. Although a small share of California's overall economy, the state's agricultural contribution is significant, producing more than 10 percent of the value of all U.S. agricultural commodities in 2014, and nearly half of U.S.-grown fruits, nuts, and vegetables.

American farmers, ranchers, and the agriculture sector as a whole are familiar with making decisions in the face of uncertainty, which arises not just from variability in weather patterns but also from fluctuations in a whole host of other factors including trade dynamics, shifts in market demands and consumer preferences, evolution of agricultural technologies, and ever-changing state and federal policies. Risk-based decision making must take each of these factors into account. Managing the risks associated with climate change will require the integration of the potential risks of climate on agricultural productivity and prices into decision making by those involved in the full value chain of agricultural production.

In assessing the risks that climate change poses to agricultural productivity, there are a whole host of variables to consider, including temperature; precipitation; availability of water resources for irrigation; CO_2 concentrations; ozone and other pollutant concentrations; and climate-driven changes in pests, weeds, and diseases. The relative importance of each of these variables will vary based on the region and the crop or livestock type. In this analysis, we focus on the impact of changing temperatures and precipitation on commercial crop yields (including grains, cotton, and oilseeds) in areas where they are currently grown in the United States. We discuss other effects in more detail in the sections that follow.

BACKGROUND

On the whole, agricultural yields have increased across the United States during the past quarter of a century due primarily to dramatic improvements in agricultural techniques and secondarily to increases in temperature and precipitation. Studies isolating climate-related effects observed to date have shown that, on average, crops were more affected by changes in temperature than by precipitation, though temperature played a greater role in increased yields in central and northern regions, with higher precipitation contributing in the southern United States (Sakurai, Iizumi, & Yokozawa 2011). However, in the past 15 years there has been a marked increase in crop losses attributed to climate events such as drought, extreme heat, and storms, with instability between years creating significant negative economic effects (Hatfield, Cruse, & Tomer 2013). Understanding the potential risks to the highly varied agricultural regions across the United States requires an assessment of both the changes in average climate variables and changes in the intensity and frequency of extremes.

Historical changes in temperature have varied both across regions of the United States, with more significant changes in the Midwest and Southwest, and by season, with greater winter and spring warming. Overall, warming has lengthened the growing season by 4 to 16 days since 1970 (U.S. Environmental Protection Agency 2012). Final spring frost is now occurring earlier than at any point since 1895, and the first fall frosts are arriving later (U.S. Environmental Protection Agency 2012). Changes in the length of the growing season can have both positive and negative effects, as they may allow farmers to have multiple harvests from the same plot. However, they may preclude certain crops, lead to significant changes in water requirements, or disrupt normal ecosystem functions such as the timing of pollination and natural protection against weeds and invasive species.

Rising temperatures are expected to further lengthen the growing season across most of the United States (by as much as a month or two over the course of the century) and reduce the number of frost days, particularly in the West (Walthall et al. 2013). While longer growing seasons may be a boon to agriculture in some regions, the overall impact on yields will also be influenced by associated increases in exposure to warmer temperatures over greater time spans. While warmer average temperatures and increased precipitation over the past few decades have contributed to increased yields, this trend is unlikely to continue as temperatures rise across much of the United States. Crop species display temperature thresholds that define the upper and lower boundaries for growth, and the current distribution of crops across the United States corresponds to temperatures that match their thresholds (Hatfield et al. 2014). The impacts on yield are nonlinear as temperatures reach and then exceed a crop's threshold. When paired with declining precipitation and increased evaporation in areas like the Southwest and southern Great Plains, warmer temperatures result in even greater declines in yield. In most regions of the United States, optimum temperatures have been reached for dominant crops, which means that continued warming would reverse historic gains from warmer temperatures and instead lead to reduced yields over time. As temperatures increase over this century, crop production areas may shift to follow the temperature range for optimal growth.

Rising temperatures and shifting precipitation patterns will also affect productivity through altered water requirements and water-use efficiency of most crops. The differential effect of these various factors will lead to regional production effects that alter regional competitiveness, potentially altering the agricultural landscape significantly by midcentury.

Changes in average conditions will be compounded by changes in extremes on a daily, monthly, and seasonal scale (Schlenker & Roberts 2009) and by changing intensity and frequency of extreme weather events (Seneviratne et al. 2012). Many extreme weather events of the past decade are outside of the realm of experience for recent generations, and, as we've seen, these events can have devastating effects. The drought that plagued nearly two thirds of the country for much of 2012 was the most extensive to affect the United States since the 1930s, resulting in widespread crop failure and other impacts estimated to have had a cost of $30 billion, with states in the U.S. heartland—Nebraska, Iowa, Kansas, South Dakota—experiencing the greatest impacts as maize and soybean yields were severely reduced, dealing a serious blow to the states' economies (NOAA 2013a). Temperature fluctuations need not be long in duration to cause widespread destruction. In 2008, heavy rain and flooding, with up to 16 inches in parts of Iowa, caused significant agricultural losses and property damage in the Midwest totaling more than $16 billion (NOAA 2013b).

Changing frequency, severity, and length of dry spells and sustained drought can significantly reduce crop yields. At their most extreme, crop death and reduced productivity due to drought can result in billions of dollars of damage; the 1988 drought that hit the central and eastern United States resulted in severe losses to agriculture and related industries totaling nearly $80 billion (NOAA 2013a). As the IPCC notes, it is not possible to attribute historic changes in drought frequency to anthropogenic climate change (Romero-Lankao et al. 2014). However, observations of emerging drought trends are consistent with projections of an increase in areas experiencing droughts in several regions of the United States (Walthall et al. 2013). There has been no overall trend in the extent of drought conditions in the continental United States, although more widespread drought conditions in the Southwest have been observed since the beginning of the twentieth century (Hoerling et al. 2012a; Georgakakos et al. 2014). Summer droughts are projected to become more intense in most of the continental United States, with longer-term droughts projected to increase in the Southwest, southern Great Plains, and parts of the Southeast (Cayan et al. 2010; Wehner et al. 2011; Dai 2012; Hoerling et al. 2012b; Georgakakos et al. 2014; Walsh et al. 2014).

Excess precipitation can be as damaging as too little precipitation, as it can contribute to flooding, erosion, and decreased soil quality. Surface runoff can deplete nutrients, degrading critical agricultural soils, and contribute to soil loss, which reduces crop yields and the long-term capacity of agricultural lands to support crops. In some critical producing states such as Iowa, there have been large increases in days with extremely heavy rainfall even though total annual precipitation has remained steady (Hatfield et al. 2013). Greater spring precipitation in the past two decades has decreased the number of days for agricultural field operations by more than three days when compared to the previous two decades, putting pressure on spring planting operations and increasing the risk of planting on soils that are too wet, reducing crop yields and threatening the ability of soils to support crops in the long-term (Hatfield, Cruse, & Tomer 2013). Greater rainfall quantities and intensity across much of the northern United States are expected to contribute to increased soil erosion (Pruski & Nearing 2002).

The projected higher incidence of heat, drought, and storms in some regions will influence agricultural productivity. The degree of vulnerability will vary by region and will depend on both the severity of events and adaptive capacity. Due to projected increases in extreme heat, drought, and storms, parts of the Northeast and Southeast have been identified as "vulnerability hotspots" for corn and wheat production by 2045, based on expected exposure and adaptive capacity, with increased vulnerability past midcentury (Romero-Lankao et al. 2014). Livestock production is also vulnerable to temperature stresses, as animals have limited ability to cope with temperature extremes, and prolonged exposure can lead to reduced productivity and excessive mortality. These effects increase the production cost associated with all animal products, including meat, eggs, and milk.

Extremes that last for only short periods are still often critical to productivity because annual agricultural output may be driven largely by conditions during narrow windows of time when crops and livestock undergo important developments. The impact of variability in precipitation and water resource availability as well as temperature extremes will depend on the timing of such events in relation to these critical periods. Warmer spring temperatures within a specific range may accelerate crop development, but extremely high temperatures during the pollination or critical flowering period can reduce grain or seed production and even increase risk of total crop failure (Walthall et al. 2012). Warmer nighttime temperatures during the critical grain, fiber, or fruit production period will also result in lower productivity and reduced quality. Such effects were already noticeable in 2010 and 2012, as high nighttime temperatures across the Corn Belt were responsible for reduced maize yields. With projected increases in warm nights, yield reductions may become more prevalent (Walthall et al. 2012). Fewer days with cold temperatures can also have significant effects, reducing the frequency of injury from chilling in some cases, while in others yields may be negatively affected as chilling requirements for some crops are not satisfied. Many fruit and nut tree species must be exposed to the winter chill to generate economically sufficient yields. The state of California is home to 1.2 million hectares of chill-dependent orchards, supporting an estimated $8.7 billion industry. With warmer temperatures expected by the middle to the end of this century, one study concludes that conditions will not be sufficient to support some of California's primary fruit and nut tree crops (Luedeling, Zhang, & Girvetz 2009).

Although the effect is less well understood than temperature- and precipitation-related impacts, rising CO_2 concentrations are expected to affect plant growth and therefore agricultural yields. Elevated atmospheric CO_2 concentrations stimulate photosynthesis and plant growth, with some plant species (e.g., C_3 crops such as wheat, cotton, soybean) exhibiting a greater response than others (e.g., C_4 crops including maize) (Leakey 2009). Increased atmospheric CO_2 since preindustrial times has enhanced water-use efficiency and yields, especially for C_3 crops, although these benefits have contributed only minimally to overall yield trends (Amthor 2001; McGrath & Lobell 2013). Experiments and modeling indicate that the impact of CO_2 on yields depends highly on crop species, and even subspecies, as well as on variables such as temperature, water supply, and nutrient supply. The interactions between CO_2 concentrations and these variables are nonlinear and difficult to predict (Porter et al. 2014). Elevated CO_2 concentrations can also increase weed growth rates and alter species distribution, and there is some indication that elevated CO_2 may contribute to a reduction in the effectiveness of some herbicides (Archambault 2007).

An important consideration for determining the impacts of climate change on U.S. agriculture is the degree to which farmers, ranchers, and the industry as a whole can adapt to changes over time. Agriculture is a complex system and has proved to be extremely adept at responding to changes over the past 150 years, though these adaptations were made during a period of relative climatic stability. Producers have continually adapted management practices in response to climate variability and change by using longer-maturing crop varieties, developing new cultivars, planting earlier, introducing irrigation, or changing the type of crop altogether (Olmstead & Rhode 1993, 2011).

However, the effectiveness of strategies used in the past may not be indicative for the types of changes expected in the future. Technological improvements, for example, improve yields under normal conditions but may not protect harvests from extremes expected in the future (Schlenker, Roberts, & Lobell 2013), such as increased drought in the Southwest and southern Great Plains or increased flooding in the Midwest and Northeast. Catastrophic crop or livestock losses are likely to affect the financial viability of production enterprises in a fundamentally different way than moderate losses over longer periods of time. In addition, many adaptive actions may be costly (e.g., requiring increased energy consumption) or constrained by climate change (e.g., increasing groundwater use may not be an option in areas with declining precipitation) (Romero-Lankao et al. 2014). Decisions about future adaptive action will need to take into account the potential risks of climate-related damage and the costs of adaptation, as well as complex changes in domestic and international markets and policies, all of which will determine the cost of doing business.

OUR APPROACH

To quantify the potential impacts of climate change on agricultural production, we rely on statistical studies that isolate the effect of temperature and rainfall on crop yields in the United States. Because there are strong cross-county patterns in crop yields, as well as strong trends over time (that may differ by location), we rely on studies that account for these patterns when measuring the effects of climate variables. Schlenker and Roberts (2009) provide nationally representative estimates that satisfy these criteria, which we use to construct quantitative projections. They examine county-level agricultural production during the period 1950–2005 and identify the incremental influence of temperature and rainfall variability on maize, soy, and cotton yields using data collected by the U.S. Department of Agriculture's National Agricultural Statistical

Service. While they focus their analysis on the eastern United States, they also provide parallel results for the western United States, which we also utilize. To estimate yield impacts on wheat, we apply a similar approach to yield data from the same source (see appendix B). We also consider how projections change when future adaptation is modeled explicitly by linking the results from Schlenker and Roberts to an analysis by Burke and Emerick (2013), who use similar econometric strategies to measure rates of agricultural adaptation in the United States (see part 5).

Figure 6.1 displays the temperature impact function for maize yield. In general, rising daily temperatures increase yields slightly until a breakpoint is reached, after which higher daily temperatures dramatically reduce yields. For maize, soy, and cotton, these breakpoints occur respectively at 84°F, 86°F, and 90°F.

This nonlinear response has been broadly replicated in multiple studies that are more local in character and is consistent with quadratic temperature responses in studies that use seasonal mean temperature. Seasonal precipitation has a nonlinear inverse-U-shaped relationship with yields (figure 6.2), again broadly consistent with local studies.

Schlenker and Roberts assess whether there is evidence that farmers adapt by examining whether there are changes in the sensitivity of crop yields to temperature over time. They find that the relationship between heat and yields has changed slightly since 1950, providing only weak evidence of adaptation. This finding is consistent with a more detailed analysis on the evolution of heat tolerance in maize in Indiana counties during the period 1901–2005 (Roberts & Schlenker 2011) and analysis of how yields in the eastern United States have responded to long-term trends in temperatures during the period 1950–2010 (Burke & Emerick 2013). Thus, while there is evidence that farmers are adapting over time, the evidence indicates that this process is extremely slow.

Schlenker and Roberts also look for evidence of adaptation by examining if counties that are hotter on average (in the Southeast) or drier and/or hotter on average (in the West) have a different sensitivity to climate. They find strong evidence that crop yields in counties in the South or in the West are less sensitive to temperature, suggesting that these locations have adapted somewhat to their local climatic conditions, probably through the adoption of heat-tolerant cultivars and/or irrigation (Butler & Huybers 2013). These adaptations come at a cost, such as lower average yields (Schlenker, Roberts, & Lobell 2013), but they might be more consistently adopted in the future in the Midwest and East if rising temperatures make them cost-effective strategies in these regions.

Schlenker and Roberts are unable to account for the effect that rising CO_2 concentrations have on agricultural yields because gradual trends in CO_2 cannot be statistically distinguished from other trends (e.g., technological

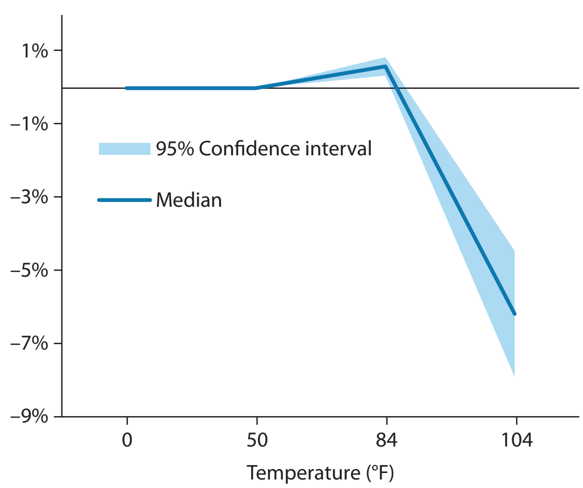

FIGURE 6.1. **Impact Function: Temperature and Maize Yields**

Observed change in maize yields (percent) vs. daily temperature (degrees Fahrenheit)

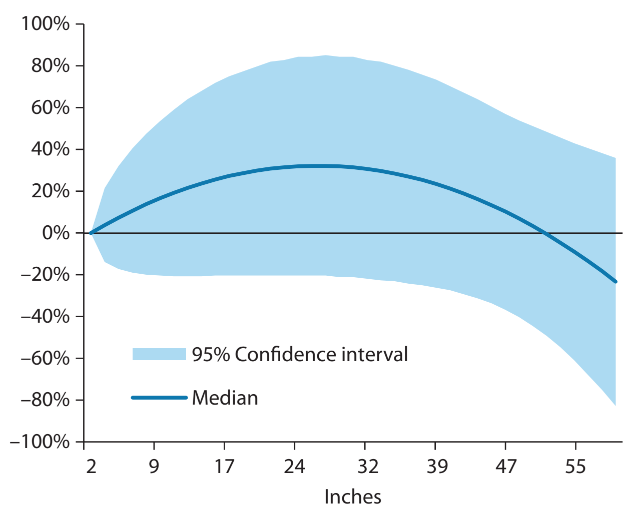

FIGURE 6.2. **Impact Function: Precipitation and Maize Yields**

Observed change in maize yields (percent) vs. seasonal precipitation (inches) progress). Thus, to account for increasing CO_2, we must draw on a body of literature that combines field experiments in CO_2 enrichment with simple models. We obtain estimates for the incremental effect that CO_2 enrichment has on yields for different crops from McGrath and Lobell (2013), who collect results from multiple field experiments and use these results to construct estimates for the effect of CO_2 fertilization on U.S. crops.

To assess potential future impacts of climate change on national agricultural production, we simulate changes in production of major crop varieties (maize, wheat, soybeans, and cotton) under different climate scenarios relative to a future in which the climate does not drive economic changes after 2012—although other social and economic trends are assumed to continue. Within each scenario, we account for uncertainty in climate models, weather, and statistical results, causing our projection to be a probability distribution of potential outcomes at each moment in time.

When we consider the potential impact of changes in temperature, precipitation, and CO_2 fertilization on national yields, we find that the value of total production generally declines as early as the period 2020–2039—even under RCP 2.6—although the range of *likely* outcomes spans positive values through 2099 under all scenarios (table 6.1). Under RCP 8.5, total production is *likely* to change by −14 percent to +7 percent by midcentury and −42 percent to +12 percent by late century, with a 1-in-20 chance that late-century changes are below −56 percent or exceed +19 percent of current production. Impacts on maize are generally negative throughout all periods because maize is strongly heat sensitive and benefits least from CO_2 fertilization, while impacts on wheat are overwhelmingly positive because wheat benefits more from CO_2 fertilization than it is harmed by heat. Impacts on cotton and soybeans are about as likely to be positive as negative until late century in RCP 8.5, when they become generally negative. The *likely* ranges for all crops are shown in table 6.1.

Projected changes are smaller in magnitude for RCP 4.5 and RCP 2.6, and the distribution of projected changes is more skewed toward negative yield changes relative to RCP 8.5. The *likely* range of late-century production changes for total production spans −25 percent

TABLE 6.1 Impacts of future climate change on U.S. agricultural yields with CO_2 fertilization

Crop Type	*RCP 8.5*			*RCP 4.5*			*RCP 2.6*		
	1 in 20 Less Than (%)	*Likely (%)*	*1 in 20 Greater Than (%)*	*1 in 20 Less Than (%)*	*Likely (%)*	*1 in 20 Greater Than (%)*	*1 in 20 Less Than (%)*	*Likely (%)*	*1 in 20 Greater Than (%)*
Maize									
2080–2099	−84	−73 to −18	−8.1	−64	−44 to −2.8	1.9	−27	−19 to 0.4	2.8
2040–2059	−39	−30 to −2.3	2.8	−34	−25 to 0.1	3.6	−23	−18 to −1.0	1.3
2020–2039	−19	−15 to 4.3	12	−19	−15 to 5.2	9.7	−21	−14 to −3.1	0.4
Wheat									
2080–2099	8.6	19 to 42	50	−1.1	4.7 to 15	17	−2.6	−0.9 to 4.4	5.3
2040–2059	3.0	6.0 to 14	17	1.0	3.7 to 10	12	−0.8	0.6 to 5.1	6.2
2020–2039	0.6	1.8 to 5.6	8.3	−0.3	1.2 to 6.5	7.7	−0.9	0.2 to 4.4	5.3
Oilseeds									
2080–2099	−74	−56 to 18	29	−55	−30 to 8.6	16	−18	−13 to 6.3	8.4
2040–2059	−23	−16 to 11	17	−24	−15 to 7.6	14	−15	−8.8 to 5.8	9.9
2020–2039	−9.7	−6.6 to 9.9	15	−15	−10 to 6.9	13	−16	−7.4 to 3.8	6.8
Cotton									
2080–2099	−74	−52 to 16	31	−38	−18 to 9.8	18	−17	−9 to 3.0	5.7
2040–2059	−20	−12 to 13	18	−15	−7.3 to 8.0	13	−15	−7.3 to 4.9	8.6
2020–2039	−7.7	−3.6 to 5.6	7.8	−8.9	−4.8 to 5.8	9.2	−11	−5.4 to 4.3	6.3

Note: Percentage change from 2012 production levels for maize, wheat, oilseeds, and cotton.

to +6 percent for RCP 4.5 and −11 percent to +3 percent for RCP 2.6. The skewed distribution is most apparent when considering 1-in-20 outcomes: production changes below −43 percent or above 10 percent for RCP 4.5 and below −17 percent or above 5 percent for RCP 2.6. The skewed distribution of total production is mainly driven by maize and soy, which have especially skewed outcomes with a 1-in-20 chance that yields are below −64 percent and −55 percent, respectively, in RCP 4.5 by late century. The skewness for total production in RCP 4.5 is sufficiently large that potential downside losses are similar in magnitude to downside losses in RCP 8.5; however, in RCP 4.5 there is a lower probability of ending up with the largest losses.

Across all RCPs, the distribution of potential yields broadens over time. The rate of spreading increases dramatically with increasing emissions. For total production, the late-century *very likely* range spans 15 percentage points in RCP 2.6 and widens to span 31 and 54 percentage points in RCP 4.5 and 8.5, respectively (figure 6.3). Climate

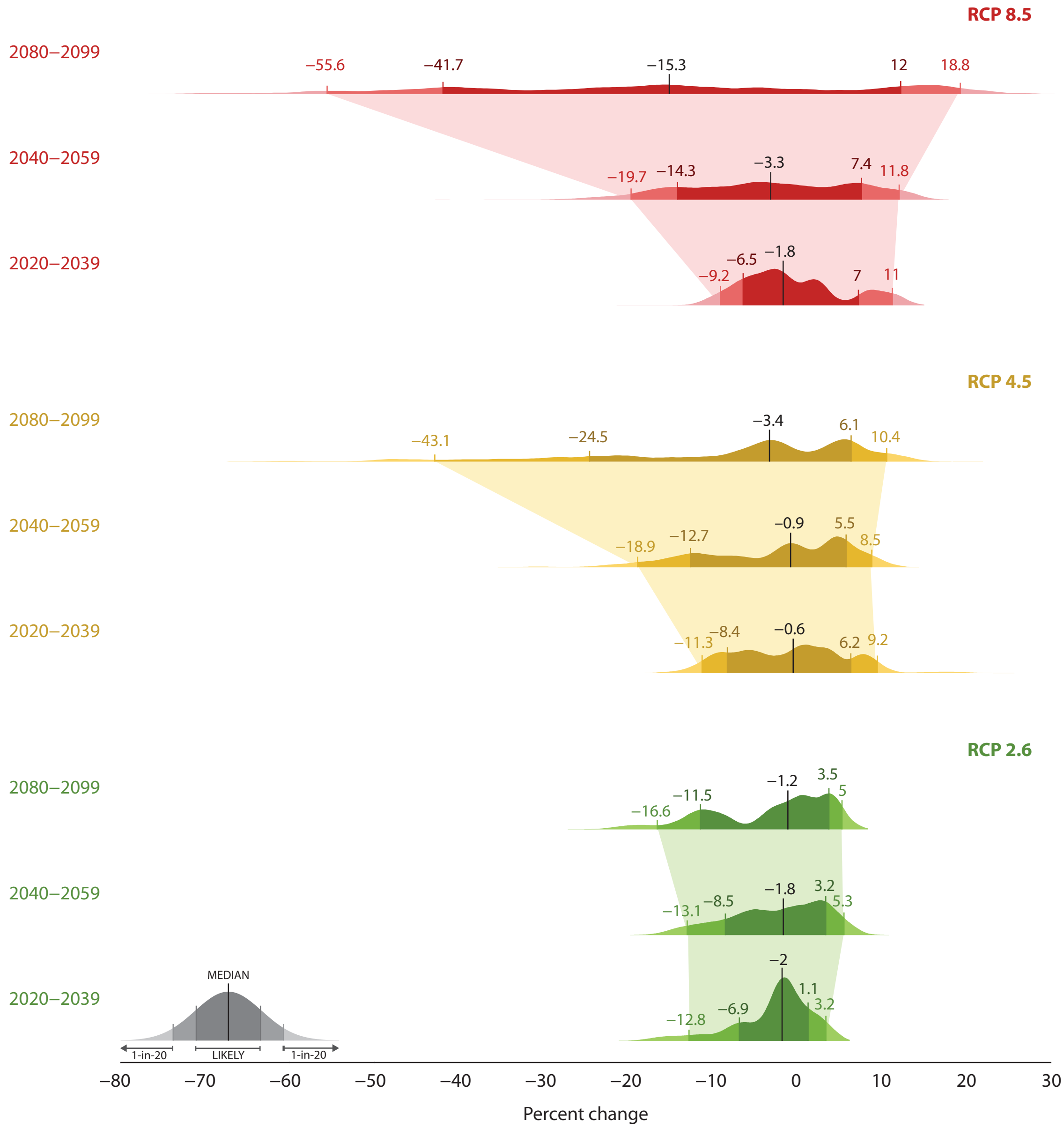

FIGURE 6.3. **Change in National Yield of Grains, Oilseeds, and Cotton**

Percent change, including CO_2 fertilization change not only decreases expectations for national production but also increases uncertainty regarding future national production in a warming world.

In percentage terms, the spatial distribution of projected impacts is uneven across the country, with the South and East regions suffering the largest projected yield losses while the Rockies, Northwest, and northern Great Plains regions achieve yield gains in the median RCP 8.5 projection (figure 6.4). The eastern United States is hardest hit primarily because the dose-response function is more sensitive to extreme heat in the East, in part because irrigation infrastructure is not as widespread as in the West (Schlenker & Roberts 2009). The Southeast suffers the largest percentage losses because the dose-response function is sensitive to extreme temperatures and because southern counties experience the highest number of additional extreme temperature days in future projections. Projected yields in the Rockies, Northwest, and northern Great Plains benefit from both moderate warming and moderate wetting from a current climate that is both cool and dry. Projected changes in total national output are dominated by production losses in central Midwest states that are not heavily irrigated, that warm substantially, and that currently have large land areas dedicated to high-yield production.

The effects noted above are described in terms of average changes over 20-year intervals. These averages are useful for describing persistent economic changes in future periods, but they mask short-lived events that may only last a year or two but have substantial economic consequences. Within each 20-year window, the likelihood of extreme annual events, such as a very low-yield year, evolves with the climate. One way to describe how the likelihood of extreme events changes is to examine how frequently we expect to experience years that are as damaging as the worst year experienced during two decades of recent history, a so-called 1-in-20 year event. In figure 6.5, we plot the estimated number of years that will have yield losses larger than historically observed 1-in-20 year losses. For each year, we plot the expected number of these extreme years that will be experienced in the 20 years that follow; that is, we plot what the immediate future looks like to an individual in a given year. For a long-term investor with a 20-year time horizon, these are expected risks to take into account. By 2030, in all scenarios, production losses that used to occur only once every 20 years will be expected to occur roughly five times in the following 20 years. By 2080, these events will be occurring roughly eight times every 20 years in RCP 4.5 and 12 times every 20 years in RCP 8.5.

These projections suggest there is a possibility that national yields will be higher in the future, with the benefits of CO_2 fertilization counterbalancing the adverse effects of extreme heat. We advise caution in interpreting these results, as the magnitude of carbon fertilization effects have not been measured empirically with the same level of consistency as temperature and rainfall effects (Long et al. 2006), and they have not been measured empirically in nationally representative samples (McGrath & Lobell 2013). Thus, we also consider the distribution of potential yield changes due only to temperature and precipitation changes—not because the CO_2 fertilization effect is likely to be zero, but because separating the effect of CO_2 fertilization allows evaluation of how large these uncertain effects must be to offset temperature and rainfall effects. When the effect of CO_2 fertilization is removed, agricultural output declines much more dramatically in projections that use only temperature and precipitation changes (table 6.2 and figure 6.6). The likely range of late-century losses in RCP 8.5 are unambiguously negative and large, spanning 20 to 59 percent for total production. The effect of removing CO_2 fertilization has different effects for different crops, although in all cases removing CO_2 fertilization causes projected losses to be larger. It is unlikely that losses this large will occur, as carbon fertilization will offset some of these losses, as it did in our main projections, so these estimates should be considered a worst-case scenario for the situation where the benefits from carbon fertilization have been overestimated.

It is important to note that these estimates assume that the national distribution of crop production remains fixed relative to the period 2000–2005. It is extremely likely that farmers' decisions regarding what they plant will change as they observe their climate changing, but this response could not be evaluated here because systematic analysis of this response is absent from the body of existing research. We hope that future analyses will incorporate this response, and we will update our projections accordingly.

Prior analyses have not examined how planting decisions change in response to the climate, although recent work has examined how farmers who always plant the same crop adapt to changes in their local climate over time. We consider how these results can be incorporated into our analysis in part 5.

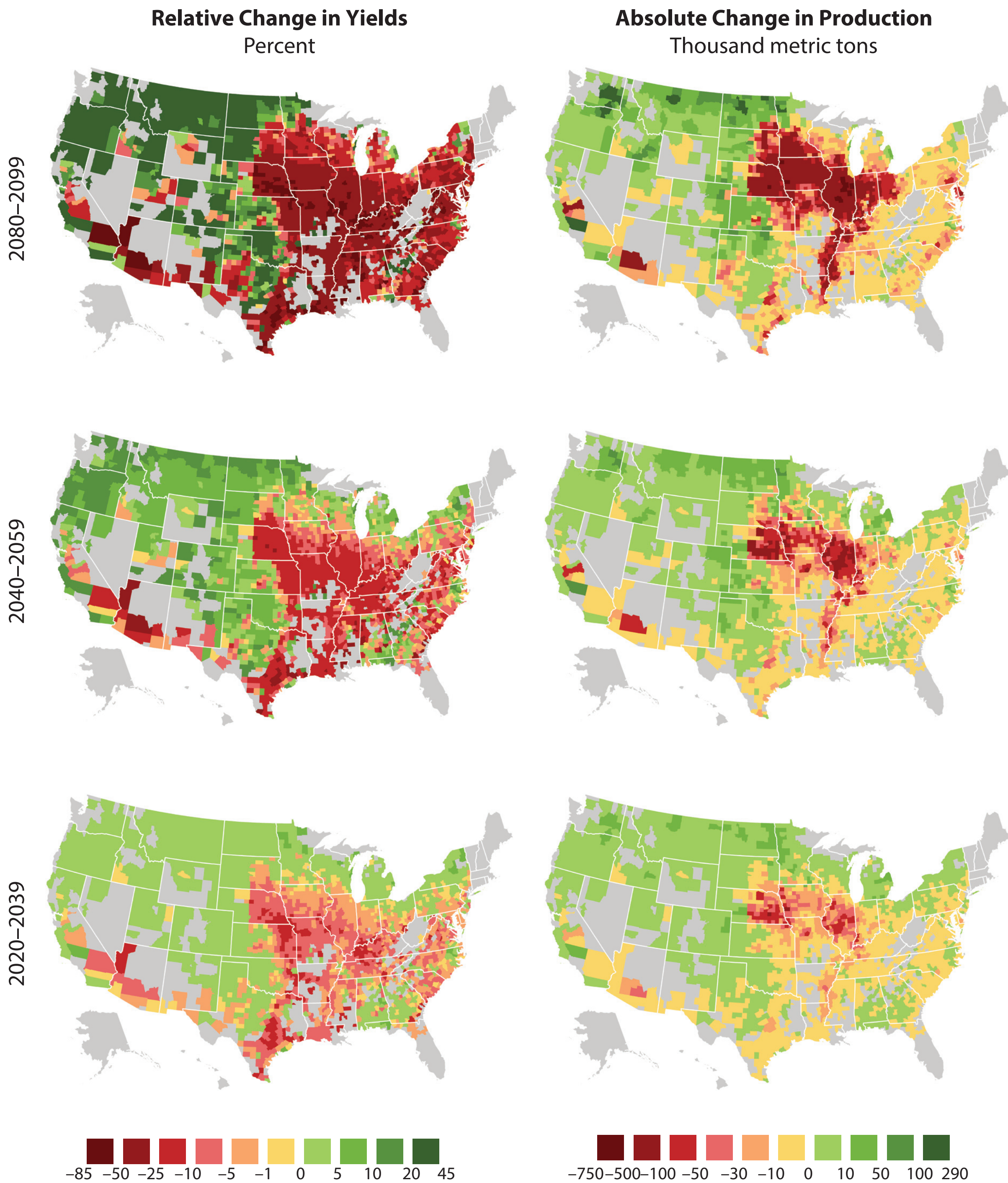

FIGURE 6.4. **Projected Change in Grain, Oilseed, and Cotton Yields by County**

RCP 8.5 median projection; gray counties are those where no grain, oilseed, or cotton production currently occurs

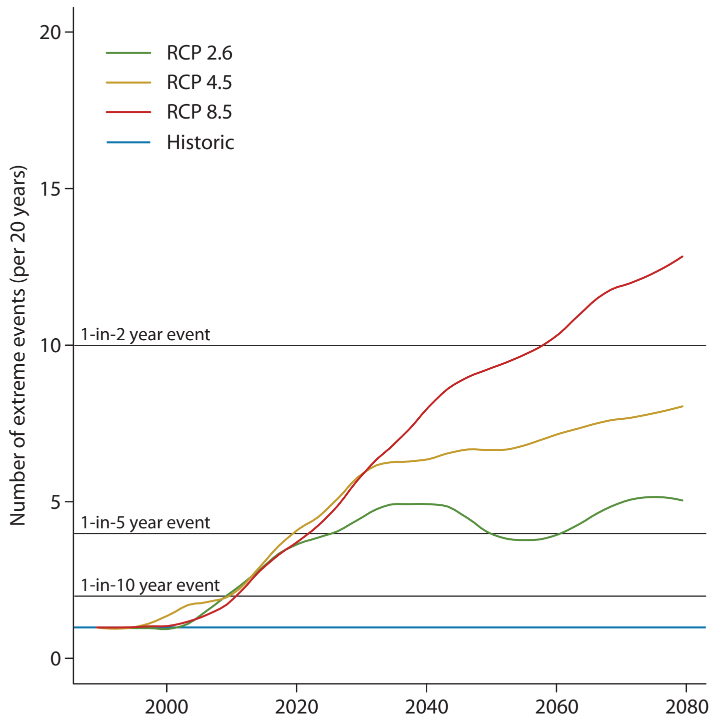

FIGURE 6.5. **Projected Change in the Frequency of National Yield Losses Equal to or Worse than Historical 1-in-20 Year Losses**

TABLE 6.2 Impacts of future climate change on U.S. agricultural yields without CO_2 fertilization

Crop Type	*RCP 8.5*			*RCP 4.5*			*RCP 2.6*		
	1 in 20 Less Than (%)	*Likely (%)*	*1 in 20 Greater Than (%)*	*1 in 20 Less Than (%)*	*Likely (%)*	*1 in 20 Greater Than (%)*	*1 in 20 Less Than (%)*	*Likely (%)*	*1 in 20 Greater Than (%)*
Maize									
2080–2099	−87	−76 to −29	−22	−66	−47 to −7.5	−3.6	−28	−20 to −0.8	1.5
2040–2059	−41	−33 to −7.1	−2.4	−36	−28 to −3.2	0.1	−25	−19 to −2.7	−0.5
2020–2039	−21	−16 to 2.5	9.4	−20	−16 to 3.7	8.0	−22	−15 to −4.3	−0.9
Wheat									
2080–2099	−27	−20 to −7.0	−4.0	−15	−9.8 to −1.5	−0.8	−6.2	−4.7 to 0.4	0.9
2040–2059	−11	−8.6 to −2.9	0.1	−8.2	−6.0 to 0.1	0.7	−6.0	−4.7 to −0.5	−0.2
2020–2039	−4.9	−3.9 to −0.9	2.0	−4.6	−3.3 to 1.9	2.5	−4.5	−3.7 to 0.4	0.9
Oilseeds									
2080–2099	−82	−70 to −20	−14	−61	−40 to −6.6	−0.3	−21	−16 to 2.2	4.2
2040–2059	−33	−27 to −4.0	0.7	−31	−23 to −2.5	3.2	−19	−14 to 0.0	3.9
2020–2039	−15	−12 to 4.0	8.5	−19	−14 to 2.4	8.3	−19	−11 to −0.1	2.6
Cotton									
2080–2099	−83	−68 to −24	−15	−47	−30 to −6.4	0.5	−21	−13 to −1.2	1.5
2040–2059	−31	−24 to −3.7	0.3	−23	−16 to −2.8	1.3	−19	−13 to −1.1	2.5
2020–2039	−13	−9.4 to −0.8	1.2	−13	−9.1 to 0.8	4.0	−14	−9.3 to 0.0	1.9

Note: Percentage change from 2012 production levels for maize, wheat, oilseeds, and cotton.

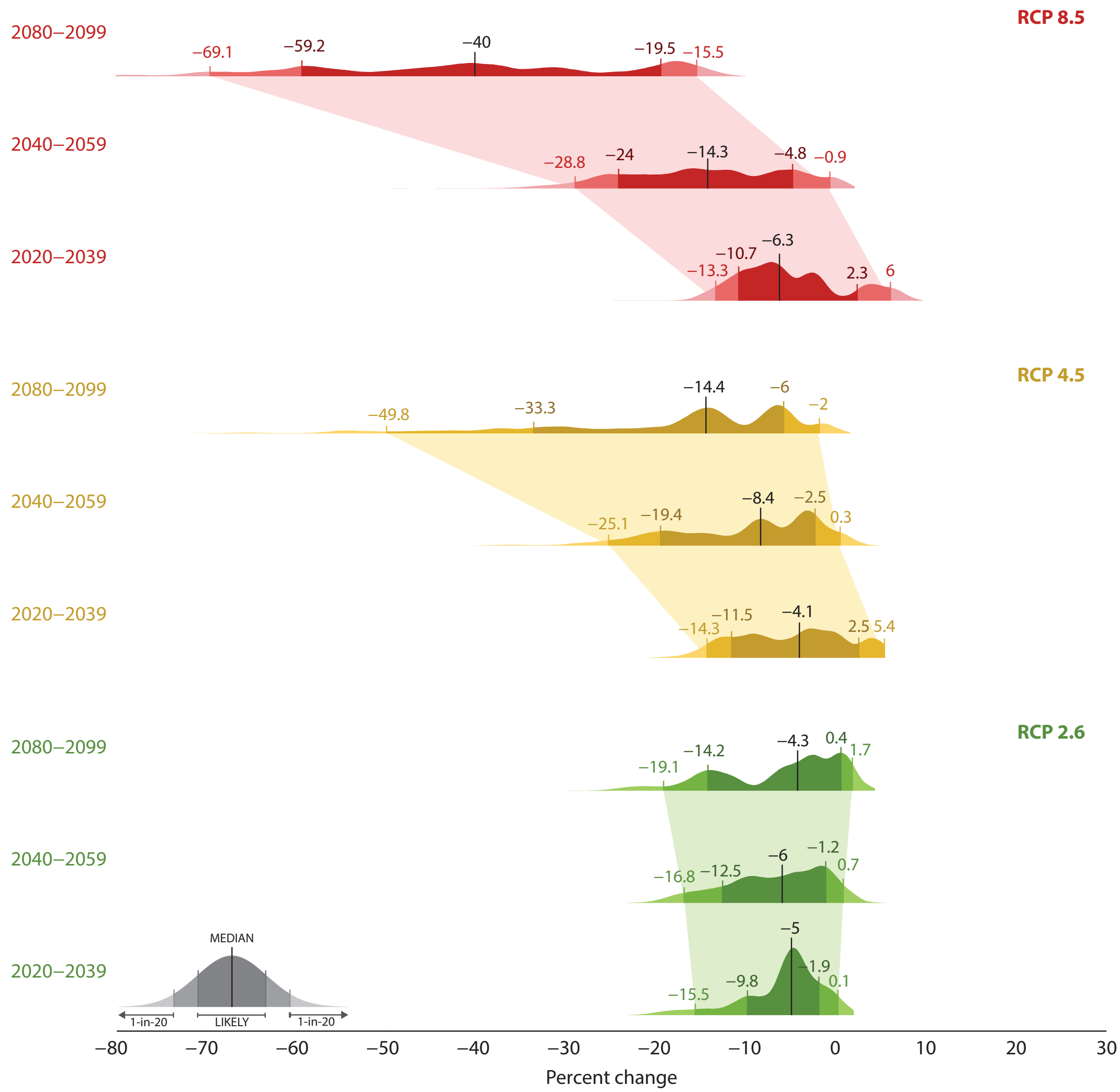

FIGURE 6.6. **Change in National Yield of Grains, Oilseeds, and Cotton**

Percent change, not including CO_2 fertilization

OTHER IMPACTS

There is a whole host of impacts that we were not able to include in this round of our analysis. We discuss some of them in this section.

Water Resources

Changing climate—including shifting precipitation patterns and greater frequency and intensity of precipitation extremes like heavy rainfall and drought in some regions—are likely to affect water resource availability, with wide-ranging implications for the U.S. agricultural sector and crop production in particular.

While irrigation reduces the risk from variable seasonal rainfall, producers that rely on irrigation to maintain yields may be at greater risk from volatility in cost and availability of water supplies. Climate change will have important implications for the extent and distribution of future U.S. irrigated crop production. Although only 7.5 percent of all U.S. cropland and pastureland are irrigated, farms that use irrigation accounted for

55 percent of the total value of crop sales in 2007, the last year for which U.S. Department of Agriculture census data are available (U.S. Department of Agriculture 2010). Irrigated agriculture accounts for more than a third of the nation's freshwater withdrawals and approximately 80 to 90 percent of overall consumptive use (Kenny et al. 2009). Nearly three quarters of irrigated acreage is in the western United States, though in recent decades much of the expansion in irrigated acreage has occurred in the eastern areas.

Reduced water availability for agriculture may lead to contraction in irrigated acreage in some areas, particularly in the western United States (Elliot et al. 2013). Warmer temperatures at the same time will also increase crop water needs and demand for irrigation, although increasing CO_2 concentrations can also increase water-use efficiency of some crops (Hatfield et al. 2013; Elliott et al. 2013; Prudhomme et al. 2013; Wada et al. 2013). Irrigation, which has traditionally been relied on to offset the negative effect of high temperatures, has been particularly effective in areas with intensive cultivation and irrigation such as the Corn Belt (Sakurai, Iizumi, & Yokozawa 2011). Such strategies may not be available or will be much more costly in regions with increased water scarcity where the cost of irrigation is likely to increase, as are energy costs associated with irrigation, including for water pumping.

Ozone Pollution

Carbon dioxide is not the only ambient pollutant that affects plant growth. Emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) from farm processes and industrial sources react to form ground-level ozone (O_3), which can damage vegetation by reducing photosynthesis and other important physiologic functions resulting in stunted crops, decreased crop quality, and decreased yields (Mills et al. 2007). High temperatures increase ozone formation, especially during the warm "ozone season" of May to September (Bloomer et al. 2009). The impacts on a range of U.S. agricultural crop yields is an area of emerging study; initial studies indicate that the impacts of elevated ozone concentrations are evident for soybean crops in the Midwest, with annual yield losses in 2002–2006 estimated at 10 percent (Fishman et al. 2010). The interactions between elevated ozone and CO_2 concentrations have been found to dampen these effects, with ozone partially counteracting CO_2 fertilization. More study is necessary to understand the interactions between CO_2, ozone, and temperature on a variety of species.

Weeds, Disease, and Pests

Agriculture is a complex system, and the mechanisms through which climate can affect productivity are many. While changing climatic conditions affect crop yield directly, they also affect a whole array of other competing and complementary organisms that have varying effects on crop yields. Changes in temperature and precipitation patterns, combined with increasing atmospheric CO_2, change weed-infestation intensity, insect population levels, the incidence of pathogens, and potentially the geographic distribution of all three.

The relationship between climate change and agricultural crop yield losses due to increased competition from weeds, for example, is not fully understood because of the complex relationships between temperature, CO_2 concentration, and crop-weed interactions, as well as artificial factors such as herbicide use (Archambault 2007). Weeds are generally hearty species, and several weeds benefit more than crops from higher temperatures and CO_2 levels (Ziska 2010). The geographic distribution of native and invasive weeds will likely be extended northward as temperatures warm, exposing farms in northern latitudes to new or enhanced threats to crop productivity from weeds like privet and kudzu, already present in the South (Bradley, Wilcove, & Oppenheimer 2010; Ziska 2010). Weed control costs the United States more than $11 billion a year, with most of that spent on herbicides. Use of herbicides is expected to increase as several of the most widely used herbicides in the United States, including glyphosate (also known by the brand name Roundup), have been found to lose efficacy on weeds grown at CO_2 levels projected to occur in the coming decades (Ziska, Teasdale, & Bunce 1999).

Climate change is also expected to affect the geographic ranges of specific species of insects and diseases across regions of the United States, potentially altering yield losses as a result. Changes in average temperature can result in gradual shifts in geographic distribution as earlier spring and warmer winters affect species overwintering and survival. In wet years, high humidity can

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Although for the purposes of this book we isolate our analysis of climate impacts to those that occur within the United States, the global nature of food production cannot be overlooked (Roberts & Schlenker 2013). The response of global agricultural systems to a changing climate may mean production shifts as some regions become more or less suitable for agriculture. The effects of climate on crop and food production are already evident in several key producing regions of the world, with recent periods of rapid food and cereal price increases following climate extremes (Porter et al. 2014). By the 2030s global average yields will *likely* be negatively affected, with reductions *more likely than not* to be as much as 5 percent beyond 2050 and *likely* by the end of the century (Porter et al. 2014). The reductions will coincide with growing global demand, which is projected to increase by approximately 14 percent per decade until midcentury (Alexandratos & Bruinsma 2012; Porter et al. 2014).

These shifts will be reflected in changing global production and commodity prices, all of which will impact U.S. producers and, in turn, how they choose to respond. Because of the complexity of estimating the impacts of climate change on global agricultural production, price, and trade, we focus on only those impacts that occur within the United States in the absence of any changes to global trade or prices. In addition, we do not model how farmers will change which crops they grow, as we lack robust empirical evidence to quantify these changes. Historical anecdotes—such as the Dust Bowl—suggest this may be an important margin for future adjustments (Hornbeck 2012; Feng, Oppenheimer, & Schlenker 2013).

In an increasingly interconnected global market, the effects of climate change on global food production and prices will affect U.S. farmers and other agricultural producers, as well as American consumers. Regional climatic changes may shift the distribution and costs of production across the globe over time, while extreme events may affect food security and price volatility. As the United States is a significant agricultural exporter, price and production shocks from extreme climate events in the United States can have reverberations globally, though the globalized system can also act as a buffer to reduce the localized effects of events in the United States (Godfray et al. 2010).

The United States imports about a fifth of all food consumed in the United States, making food prices and supply vulnerable to climate variations in other parts of the world. Climate extremes in regions that supply the United States with winter fruits and vegetables, and in particular tropical products such as coffee, tea, and bananas, can cause sharp reductions in production and increases in prices. Volatility in supplies and prices of internationally traded food commodities have a significant effect on decisions made by U.S. agricultural producers and determine prices U.S. consumers pay for such goods. Fluctuations and trends in food production are widely believed to have played a role in recent price spikes for wheat and maize, which followed climate extremes in 2008 and 2011. Between 2007 and 2008, the Food and Agriculture Organization food price index doubled; this was due to a confluence of factors, one of which was extreme weather conditions in major wheat and maize exporters including the United States, Australia, and Russia (Food and Agriculture Organization of the United Nations 2011). Such extreme events have become more likely as a result of recent climate trends and may be more frequent in the future, contributing additional volatility to an already complex global agricultural system.

The IPCC has reported that projected changes in temperature and precipitation by 2050 are expected to increase food prices, with estimates ranging from 3 to 84 percent. Projections of food prices that also account for the CO_2 fertilization effect (but not ozone and pest and disease effects) range from –30 percent to +45 percent by 2050, with price increases about as likely as not. This does not take into account variations in regional effects or the effect of extremes, which can be a major contributor

(*continued*)

to variability in productivity and prices. Compound events where extremes have simultaneous effects in different regions (as was witnessed in 2008 and 2011), driven by common external forcing (e.g., El Niño), climate system feedbacks, or causally unrelated events, may have additional negative impacts on food security and production, though there are very few projections of such compound extreme events, and the interactions between multiple drivers are difficult to predict.

Quantifying these effects, in their agricultural and economic terms, is an extremely difficult task, requiring assumptions about the myriad climate and nonclimate factors that interact to determine food security and prices, both at home and abroad. While all aspects of food security are potentially affected by climate change, including food access, utilization, and price stability, there is limited direct evidence that links climate change to food security impacts (Porter et al. 2014).

help insects and diseases flourish, with negative indirect impacts on animal health and productivity (Garrett et al. 2006, 2011). Climate affects microbial and fungal populations and distribution, the distribution of diseases carried by insects and rodents, animal and plant resistance to infections, food and water shortages, and food-borne diseases (Baylis & Githeko 2006; Gaughan et al. 2009). Regional warming and changes in rainfall distribution may change the distributions of diseases that are sensitive to temperature and moisture, such as anthrax, blackleg, and hemorrhagic septicemia (Baylis & Githeko 2006; Gaughan et al. 2009).

Livestock

Although livestock is a major component of the U.S. agricultural system, with nearly 1 million operations generating nearly half of total U.S. commodity sales, the impact of climate change on livestock production has received less study than impacts on agricultural crops. Climate change will affect the livestock sector both directly, through impacts on productivity and performance due to changes in temperature and water availability, and indirectly, through price and availability of feed grains and pasture and changing patterns and prevalence of pests and diseases (Walthall et al. 2013).

Livestock productivity will be most directly impacted by changes in temperature, which is an important limiting factor for livestock in the United States. High temperatures tend to reduce feeding and growth rates as animals alter their internal temperatures to cope; the resulting increase in animals' metabolism reduces production efficiency (André et al. 2011; Porter et al. 2014). For many livestock species, increased body temperatures 4°F to 5°F above optimum levels disrupts performance, production, and fertility, limiting an animal's ability to produce meat, milk, or eggs. Livestock mortality increases as optimums are exceeded by 5°F to 13°F (Gaughan et al. 2002). Animals managed for high productivity, including most meat and dairy animals in the United States (e.g., cattle, pigs, and chickens), are already operating at a high metabolic rate, decreasing their capacity to tolerate elevated temperatures and increasing the risk of reduced production or death (Zumbach et al. 2007).

Livestock and dairy production will be more affected by changes in the number of days of extreme heat than by changes in average temperature, though the effect of warmer average nighttime temperatures, especially multiple hot nights in a row, can exacerbate animal heat stress (Mader 2003). The negative effects of hotter summer weather will likely outweigh the benefits of warmer winters, with the potential for only about half of the decline in domestic livestock production during hotter summers to be offset by milder winter conditions (Adams et al. 1999).

The majority of American livestock raised in outdoor facilities, and therefore exposed to rising temperatures and increased heat stress, are ruminants (goats, sheep, beef and dairy cattle). Within limits, these animals can adapt to most gradual temperature changes but are much more susceptible to extreme heat events (Mader 2003). Impacts are less acute for confined operations that use temperature regulation, which house mostly poultry and pigs, though management and energy costs associated with increased temperature regulation will increase. Confined operations are not immune to the effect of rising temperatures, which can contribute to livestock heat stress. Despite modern heat-abatement strategies, heat-induced productivity declines during hot summers—including reduced performance and reproduction as well as mortality—cost the American swine industry, for example, nearly $300 million annually (St-Pierre, Cobanov, & Schnitkey 2003).

Current economic losses incurred by the U.S. livestock industry from heat stress, most from effects on dairy and beef cattle, have been valued at $1.7 billion to $2.4 billion annually. Nearly half of the losses are concentrated in a few states (Texas, California, Oklahoma, Nebraska, and North Carolina). Exposure to high-temperature events can be extremely costly to producers, as was the case in 2011, when heat-related production losses exceeded $1 billion (NOAA 2013b). Large-scale commercial dairy and beef cattle farmers are most vulnerable to climate change and the expected rise in high-heat events, particularly as these farmers are less likely to have diversified.

Other, less well-studied impacts on the livestock sector from expected climate change include indirect effects of warmer, more humid conditions on animal health and productivity through promotion of insect growth and spread of diseases. Warming is also expected to lengthen the forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al. 2010; Izaurralde et al. 2011; Hatfield et al. 2014). One study identified significant expected declines in forage for ranching in California, even under more modest climate changes (Franco et al. 2011).

Studies of the potential effects of climate change have projected the resulting effects on productivity through factors such as change in days to market and decrease in annual production. One study found that, given expected warming by 2040, days to market for swine and beef may increase 0.9 to 1.2 percent, with a 2.1 to 2.2 percent decrease in dairy milk production (Frank et al. 2001). By 2090, days to market increased 4.3 to 13.1 percent and 3.4 to 6.9 percent for swine and beef, respectively, with a 3.9 to 6.0 percent decrease in dairy production as a result of heat stress.

Relatively few economic-impact studies have estimated the costs of climate-related effects with respect to productivity and management costs of the livestock and dairy sectors, as they involve accounting for the complex and interactive direct and indirect effects, such as lowered feed efficiency, reduced forage productivity, reduced reproduction rates, and assumptions about adaptive actions such as modifying livestock housing to reduce thermal stress. In the absence of such estimates, most system-wide economic-impact assessments do not account for the potential direct costs and productivity effects of climate change on livestock, forage, and rangeland production (Antle & Capalbo 2010; Izaurralde et al. 2011).