Quantifying the Impacts of Climate Change on U.S. Corn Yields

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Corrigendum: Quantifying the Impacts of Climate Change on U.S. Corn Yields

Since its publication, the authors of the report found an error in the way "summer" was defined in the text. All references to "summer" weather as being daily temperature and rainfall during the period "June-August" were incorrect. The "summer" weather data referred to was in all cases for the period from day of year 151 to day of year 275 (inclusive)—i.e., May 31 to October 1, inclusive, for a non-leap year. Readers should note that all crop yield *calculations* are independent of this (or any) definition of "summer" because the water balance, crop growth, and yield models used weather data from every day of the year—from January 1 to December 31—therefore this error had no impact on study conclusions.

Executive Summary

Agriculture—which produces the great majority of human nourishment; directly supports an extensive international food, beverage, and entertainment supply chain; provides economically valuable fibers such as cotton; and grows the precursors for biofuels—depends on favorable climates for its success and sustainability locally, regionally, and globally. Due to many decades of intensive, successful, location-based plant breeding, most current major U.S. crops are well adapted to current local climates. Moreover, there have been strong, positive trends in yield (the amount of plant product, such as seeds or tubers, that are harvested per acre of crop) of most crops during the past 70–90 years in the United States and across the globe. Those positive yield trends were, and continue to be, brought about by improved crop-plant genetics, mechanization, and other technologies that include chemical inputs, and farmer skill.

Despite the robust, positive trends in crop yields in recent decades, and the remarkably successful plant breeding programs across the world, poor weather still negatively affects the growth of crops and the production of their desired products, such as seeds, roots or tubers, and fibers, on a regular basis. That poor weather can take the form of extremes in temperature such as cold snaps or heat waves during the growing season. It can also be expressed as excessive variation in rainfall resulting in drought or flood, including floods before a crop's growing season that prevent the planting of that crop in the first place. The exceptional wetness during the spring of 2019 in much of the Midwestern United States was a recent, costly example of preseason cropland flooding. And storms that produce damaging hail or wind, or both, can also harm or destroy crops, with the Midwestern derecho experienced during August 2020 a recent example. When such irregularities in weather cause yield shortfalls on a regional scale it can both harm the economies of agriculturally based communities within the region and impact more far-reaching supply chains of food, fiber, and biofuel with follow-on impacts to related food, energy, and economic security.

Nearly every long-term crop yield time series that displays a positive trend over time during the past several decades also expresses a skewness toward lower yields such that the largest departures from the trendline are for low yields rather than high yields. Because weather is the main driver of interannual variation in crop yield, that skewness toward low yield indicates that poor weather is more damaging to yield than good weather is beneficial. For major U.S. crops this is because the then-current crop genetics in combination with the then-current management practices set a type of “upper limit” on attainable yield, which is sometimes referred to as “yield potential”—in practice, typically about 20–30% above the then current yield-trend value. As a result, under the best of conditions, including favorable weather, optimal supply of soil nutrients, and lack of disease and insect pests, crops can at best produce yields only 20–30% above the trend line. On the other hand, especially poor weather has the potential to reduce yield to zero.

There is justified concern about the effects of recent and future climate change on agriculture both in the United States and across the globe. If, or when, climate change brings with it more frequent and/or more extreme unfavorable weather to areas of significant crop production, such as the U.S. Midwest, the potential for significant crop losses and economic impacts could be heightened. Indeed, experimental research, statistical analysis of historical crop yield data, and process-based computer simulations all indicate that human-caused climate change is already affecting crops, in some cases for the better and in other cases to the detriment of crop production. Perhaps of more importance than effects of recent climate trends on crops are the well-established possibilities for future, more extreme climate change involving more frequent and more damaging events reducing productivity of major crops, including corn, rice, wheat, soybean, cotton, and the other staples of human food, fiber, and biofuel across many geographies. In any case, we currently face considerable uncertainty about both crop responses to recent climate change and the timing and magnitudes of potentially negative effects of future modifications to climate and weather on crops.

To better understand and quantify the potential magnitude of climate change impacts on crops, an AIR process-based Crop Growth and Yield Model was used to simulate effects of observed past and projected future climate change on corn (maize) yield at high resolution throughout the U.S. Corn Belt, defined as the states of Iowa, Illinois, Indiana, Kansas, Kentucky, Michigan, Minnesota, Missouri, North Dakota, Nebraska, Ohio, South Dakota, and Wisconsin. Together, these 13 states grow nearly 90% of U.S. corn grain and produce almost 30% of the global corn crop. Corn was chosen as the study focus because it is the most valuable crop grown in the United States and because the United States is the world’s largest producer of corn. Many of the lessons learned from this study are pertinent to other major crops grown domestically and abroad.

In this study, two numerical (computer model) experiments were conducted to simulate corn yield across the U.S. Corn Belt on a spatial grid of 0.1° latitude by 0.1° longitude. Yield of model corn crops that were either rainfed, meaning that their only source of water was from precipitation, or irrigated were simulated separately. A large majority of the current U.S. corn crop is rainfed, with irrigated corn grown mainly in parts of Kansas and Nebraska.

The first numerical experiment, the *historical-weather experiment*, was designed to quantify effects of weather and climate change during the period 1974-2019 on U.S. Corn Belt corn yield. It used historically observed daily weather—precipitation amount and minimum and maximum air temperatures—processed and reported by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) as input to the crop model.

The second experiment, the *climate-change-scenario experiment,* was conducted to better quantify possible effects of projected climate change on U.S. corn yield for the period 1991–2055. That time period allowed comparison of corn yield in the last decade of the 20th century to projected yield in the middle decade of the 21st century. It used past and future climates simulated by four leading general circulation models (GCMs; sometimes also called global climate models) as input to the crop model. Inclusion of the 1991–2019 period allowed comparison of GCM-simulated climate with historical observations across the Corn Belt. The GCM results that were used were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for GCMs using atmospheric greenhouse gas concentration trajectories from the Representative Concentration Pathway (RCP) 8.5 scenario as their input. RCP 8.5 is often considered the highest plausible 21st century trajectory of greenhouse gas concentrations and is a widely used benchmark in climate change studies.

The purpose of this research was to determine (isolate) effects of variation in weather and climate on corn yield, with other factors held constant by the crop model. To accomplish this goal of isolating effects of weather/climate on crop yield, the crop model held corn genetics and other technological factors constant at circa 2019 values—i.e., the model was parameterized for circa 2019 corn yield potential across the Corn Belt. The only variables in addition to weather that were allowed to change over time were (i) the planting date in the historical-weather experiment and (ii) annual mean atmospheric carbon dioxide (CO_2) concentration in both experiments. By holding all other non-weather variables constant, the study avoided possible adaptations to future climate change, including altered crop genetics (i.e., improved germplasm) better suited to a new climate. Irrigation water was assumed to be available when needed for irrigated crops because future availability of irrigation water, from either surface water or groundwater sources, was not a topic addressed in this study. It is noted, however, that projected future atmospheric warming, and perhaps reduced summer rainfall, might increase demand for irrigation water, with that demand perhaps surpassing future available supplies.

Results of the historical-weather experiment indicated that observed weather became more *favorable* for corn over much of the Corn Belt as time progressed from 1974 to 2019. This was evident in increased modeled yields in most Corn Belt states for both rainfed and irrigated crops with crop genetics and management practices held constant. This beneficial effect of changing climate was associated at least in part with the observed summer “warming hole” over much of the Midwest in recent decades. That historical summer warming hole was characterized by summer daytime maximum air temperatures that remained constant, or even *declined*, during recent decades in parts of the Corn Belt, especially those parts supporting most of the corn production. This cooling of summer daytime maximum temperatures occurred while other parts of the United States (and much of the planet) experienced increased summer daytime maximum temperatures. The observed warming hole was accompanied by modest increases in summer rainfall over much of the Corn Belt, including several portions of that region that were responsible for significant crop production. According to the crop model, one result of even slight declines in summer maximum temperatures during recent decades is a reduction in frequency or extent of high-temperature stress on corn in parallel with reduced water demand by the crop. Reduced water demand can result in conservation of soil moisture during the summer, which in turn can reduce the likelihood of subsequent crop water stress. This, in combination with increased rainfall over much of the core of the Corn Belt, led to increased yield of modeled corn in the states growing a large majority of the U.S. corn crop.

The observed Midwestern summer warming hole—along with a warming hole over the southeastern United States during winter and spring—has been the subject of considerable previous research. While the phenomenon is well documented, its causes are not yet firmly established, although there is evidence that key (likely) drivers of the nearly constant or reduced Midwestern summer daily maximum air temperatures include some combination of altered decadal-scale oceanic oscillations, increased cloud cover, intensification of agricultural practices to drive higher yields through increased summertime crop biological activity (including enhanced transpiration), and perhaps emissions of aerosol precursors such as SO_2 (which have been on the decline since 1970).

In the climate change scenario experiment, which held corn genetics and management practices constant (e.g., planting date was held constant at the 2019 average date in each county over the period 2020–2055), and which used climates projected by the four GCMs as inputs to the crop model, the simulated corn yields across the Corn Belt during the decade 2046–2055 were 20–40% less than yields simulated during the 1991–2000 decade. There was significant variation in future climate projections between the four GCMs, and this translated into substantial variation in yield declines between 1991 and 2055 when the crop model ingested weather output from the different GCMs. In all cases, however, daily precipitation and temperature derived from the output of the four GCMs reduced modeled corn yield averaged over the decade 2046–2055 compared to the decade 1991–2000. For three of the four GCMs, the percentage drop in corn yield was greater for rainfed crops than for irrigated crops because future summer rainfall was reduced in those three models. In the absence of irrigation, those reductions in summer rainfall, which were accompanied by increased summer temperature, resulted in additional water stress. The fourth GCM projected increased summer rainfall during the coming three decades, which limited to some degree the increase in simulated future water stress. Nonetheless, future yields were projected to fall even for weather derived from the fourth GCM because detrimental effects of summer warming outweighed beneficial effects of increased summer rainfall.

Increasing atmospheric CO_2 concentration, which partially closes the pores in corn leaf surfaces through which water is lost during transpiration, conserved a small amount of soil moisture over the progression of the experimental period in the climate-change-scenario experiment. This did not, however, significantly affect modeled yield. (It is well established that increasing atmospheric CO_2 concentration has significant positive effects on several other major crops including cotton, soybean, and wheat, but more limited effects on corn.)

There were significant differences in geographic patterns of modeled future yield reductions between the climate change projections from the four different GCMs. In general, negative effects of GCM-projected climate change on modeled corn yield during the 1991–2055 period were largest in the central and southern parts of the 13-state Corn Belt. That region contains many of the counties currently growing the largest amounts of corn. The overall modeled corn response to GCM-projected climate change over the period 1991–2055, averaged across the four GCMs over the entire Corn Belt, was a *reduction* in yield of about 7% per °C summer warming in the Corn Belt.

The ability of a crop to maintain consistent yields across years—i.e., to limit year-to-year variation in yield in response to interannual variation in weather—is considered *yield stability*. Yield stability, or consistency and predictability of yield across years, supports economic stability for farming operations, including longer-term planning by growers and financers. Any climate change–induced reduction in yield stability would have the potential to (i) increase risk of economic loss during any given year, (ii) increase costs of farm operation financing (e.g., increase loan interest rates), and (iii) reduce reliability of human food, animal feed, and biofuel supply (about 40% of U.S. corn production is domestically used as feed for livestock grown for human consumption, about 35% is domestically used as feedstock for fuel ethanol production, and about 18% is exported for various uses; the remainder or about 7% includes the fraction domestically eaten by humans either as grain or as carbohydrates, oils, and other biochemical fractions extracted from the grain).

In this study, not only did the climate change scenario experiment result in a significant drop in *average* simulated corn yield across the Corn Belt during the decade 2046–2055 relative to the decade 1991–2000, but the interannual variation in yield for both rainfed and irrigated crops tended to be greater. In particular, yield stability was reduced in most major corn-producing counties during the decade 2046–2055 for three of the four GCM-based climate scenarios. Effects of the fourth GCM-based climate change scenario—the one involving increased future summer rainfall—produced a mixture of increased and decreased year-to-year variation in county-scale yield for rainfed corn in the future, but generally increased interannual variation in yield for irrigated corn in the major corn-producing counties.

The usefulness of model-based analyses of crop responses to variation in weather or changes in climate depend in part on accuracy (or representativeness) of the weather or climate data used as input to a crop model. The other key factor is realism of the crop model's response to weather. Our view is that the NOAA CPC gridded daily weather data are of high fidelity, and that our mapping of those data onto the 0.1° × 0.1° grid in the historical-weather experiment was of high quality. We therefore judge the weather data input to the crop model in the historical-weather experiment to be reliable and not a significant source of uncertainty in the results.

Conversely, the simulations of crop responses to future climate variability and change did entail significant uncertainty associated with the weather data derived from the GCMs and ingested by the crop model. In particular, discrepancies were observed when comparing GCM simulations of the Corn Belt's summer (June–August) climate during the period 1974–2019 with corresponding historical values of temperature based on weather station data analyzed by NOAA CPC. All four GCMs were driven by historical atmospheric greenhouse gas concentrations through the year 2005 and thereafter by RCP 8.5 atmospheric greenhouse gas concentration trajectories. For the most part, all four GCMs projected daily summer minimum and maximum temperatures broadly consistent with observations for most Corn Belt states through the early 2000s, but after that the GCMs generally projected temperatures exceeding the observations and more so for maximum than minimum temperature. The discrepancies between GCM temperature projections and observations were generally largest at the end of the historical period. This lack of correspondence between GCM-simulated and observation-based summer daytime temperature trends in the most recent 10–20 years is also a characteristic of some other CMIP5 GCMs as well as from some of the newer CMIP6 GCMs. The discrepancies between historical (observed) Corn Belt climate and climate simulations by the GCMs for the recent past illustrate a potentially important uncertainty in the ability of the GCMs used in this study (and other CMIP5 GCMs) to forecast the magnitude, and perhaps especially timing, of near-future Corn Belt climate change.

But even though CMIP5 GCMs contained imperfections and uncertainties, with those uncertainties varying between models, GCMs are nonetheless the best tools available to understand and forecast likely future changes in climate, with the combined results of multiple models (ensembles) generally thought to be more robust than results from individual GCMs. Continuing advances in GCMs will facilitate a more thorough and accurate view of probable future climate change in the Corn Belt, and this will reduce uncertainty surrounding likely effects of the future climate on crop yield and yield stability. In particular, it may be expected that future GCMs will better represent and simulate the observed Midwestern summer warming hole; several avenues for improvement in this area have been suggested in the scientific literature. This in turn will provide both better understanding of the causes of the historical warming hole and the possible nature and timing of its persistence or eventual disappearance, which has considerable significance for the future of crop production across the Corn Belt.

In summary, these numerical experiments indicate that *observed climate change* over the period 1974–2019 were generally *favorable* for corn yield over much of the Corn Belt. This was especially the case for rainfed corn, which accounts for a large majority of corn production in the region. On the contrary, *projected future climate change* out to the decade 2046–2055, as characterized by the four CMIP5 GCMs used under the RCP 8.5 atmospheric greenhouse gas concentration scenario, would be expected to present a *significant drag* on future yield gains. This implies that without mitigation of undesirable effects of projected climate change on crops, including adaptation by farmers and improvements to crop genetics and other technological factors, corn production (i.e., yield × area harvested) could be negatively impacted during the next several decades. As a result, Corn Belt communities economically dependent on crop production may face new, and in some instances perhaps serious, financial challenges by mid-century.

Introduction

Agriculture, more than any other significant human economic enterprise, depends on and is affected by weather and climate on all temporal and spatial scales. Considerable concern about potential negative effects of recent, and projected future, climate change on national and global agriculture is warranted. Crop production in the United States is vital to the nation's economy, both nationally and internationally, and is the basis of the country's enviable degree of short-term and long-term food security. Any effects of climate change on U.S. crops therefore can have far-reaching consequences both for the economy and fundamental human health and safety.

The value of U.S. crop production was about USD 200 billion in 2020, with corn grown for grain being the single most valuable crop (Table 1). Crop and livestock output from America's farms contribute about 1% to U.S. GDP and on-farm jobs account for about 1.3% percent of U.S. employment, but farm output supports much larger food and textile sectors—over 5% of GDP and 11% of employment—with food accounting for 13% of U.S. household expenditures (USDA, 2020a). Moreover, the financial health and stability of rural communities in crop-growing locales depend heavily on crop production.

Table 1. Value of U.S. crop production in 2020. Values for field crops are preliminary; values for fruit and nut crops are for 2019 (2020 fruit and nut crop estimates were unavailable at time of writing) (USDA, 2021)

Crop or Crop Category	Value (USD Billions)
Corn (for grain*)	61.0
Soybean	46.1
Hay	17.3
Wheat	9.3
Cotton	4.7
Total field crops	**158.6**
Total fruit and nut crops	28.8
Total vegetable crops	13.1
Total crops	**200.5**

*Excludes corn harvested for silage

In view of the importance of crop production to the United States, the significant influence weather and climate have on crops, the recent changes to climate in the United States, and scientifically based projections of further climate change in future, we designed a set of numerical experiments to answer two questions: (1) how have observed climate change of the past 45 years affected yield of corn, the country's most important crop, and (2) how might future climate change further influence corn production in the United States.

Crop Yield and Production Trends

In the United States, there have been near-continuous increases in crop yield (production in bushels divided by area harvested in acres) since 1940 (Figure 1), which sustained national food security and the vitality of many rural communities. For example, national yield gain in U.S. corn and wheat were roughly 500% and 225%, respectively, over the period 1940–2020. For both crops. the long-term trend in yield increase was approximately linear. Some key drivers of yield gains across most crops in many countries since 1940 have been improved crop-plant genetics (including greater stress tolerance in the case of corn), engineering advances in mechanization and scientific advances in agronomy, availability of fertilizers, more effective pesticides, and increased farmer skill, including the selection of improved management practices and better timing of events such as crop planting, nutrient additions, and irrigations (e.g., Tollenaar & Lee, 2002; Egli, 2008; Connor et al., 2011). Increasing atmospheric CO_2 concentration also will have made a small, continuous contribution to yield gains for many crops, especially those using the "C3" pathway of photosynthesis, which includes wheat, rice, soybean, cotton, and most fruits and vegetables (Amthor, 1998; Tubiello et al., 2007; Ziska & Bunce, 2007) and less so for crops that use the "C4" photosynthetic pathway, which includes corn, sorghum, and sugarcane (Ghannoum et al., 2000; Leakey et al., 2009). At the same time, climate change may have contributed positively or negatively to past trends in yield gains, depending on crop species and locale (Hatfield et al., 2018, 2020). Indeed, climate change may have contributed positively to yield gain during some periods, and negatively during others, even for the same crop at the same location.

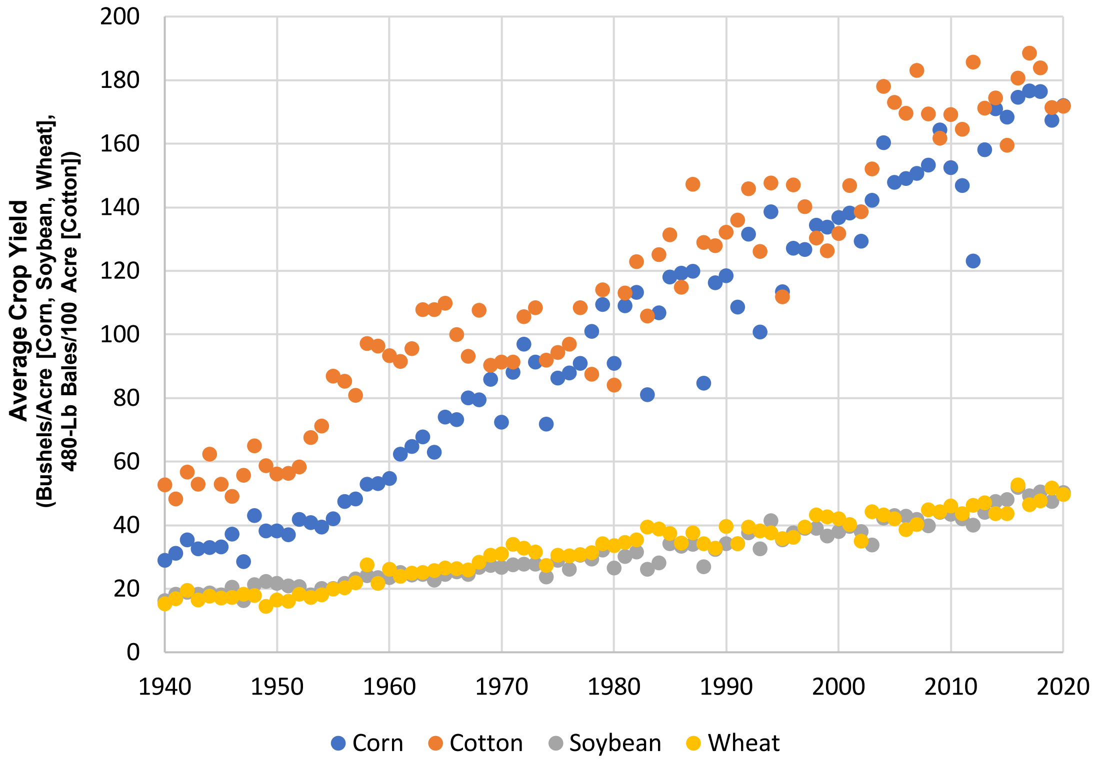

Figure 1. National average yield of the four major U.S. row crops, 1940–2020. Averaging at the national scale balances out significant spatial variation in crop yield. (Data source: USDA National Agricultural Statistics Service)

Interannual variation in yield tends to decrease with increasing spatial scale from portions of individual fields up to the national average. Hence national averages can obscure significant variation at local scales. Much, and usually most, of the year-on-year yield variation at all spatial scales is due to differences in weather, with variation in rainfall and temperature being the main drivers of yield variation. For U.S. corn, national-scale yield shortfalls (against the backdrop of the increasing yield trend) are clearly associated with extreme weather. Examples are the wet spring and early frost in 1974; large-scale droughts (lack of rain) in 1980, 1983, 1988, 2002, and 2012; extensive flooding in 1993; and a widespread cool, wet spring with hot, dry summer in 1995. It is important that, at least at the national scale, not all crops behave in lockstep year-over-year. The large drop in corn yield during 2012 was accompanied by an at-the-time record high national cotton yield, average national wheat yield, and only modest reduction in national soybean yield (Figure 1).

As indicated above, most of the major losses of yield in recent history were related to extremes in rainfall— usually too little, but also too much. This is not to say that other factors are unimportant, as extremes in temperature and physical damage from hail and wind are known to affect yield, and sometimes in dramatic ways; hail and wind generally cause physical crop damage at a more local geographic scale, whereas drought will sometimes cause crop damage across a large region. Biotic factors, including damage by insect pests and diseases, and competition from weeds, can also negatively affect yield. Even when yield shortfall is related to insects or pathogens, however, those occurrences are often associated with weather events that are directly or indirectly favorable for the insect or disease. For example, excessive wetness of the soil or crop plants resulting from abnormally high rainfall can promote growth of fungi or bacteria on crop roots, leaves, stems, or fruiting bodies. Or, warmer-than-normal winter and spring might promote survival of some insect pests and perhaps allow their activity earlier in the year.

The greater *relative* loss, or greater interannual variation, of yield during poor years at a finer geographic scale is illustrated for corn yield in McLean County, Illinois (Figure 2), the top corn-producing county in the country. The largest percentage yield deviations from the long-term, increasing trend in McLean County were associated with extreme weather in the years 1974, 1980, 1983, 1988, and 2012 as noted earlier for the national scale.

For nearly every long-term crop yield time series there is a skewness toward lower yields; the worst years are more damaging than the best years are beneficial because the best years cannot exceed the genetic potential of the crop while poor weather, disease, and pests can reduce yield to zero. This is especially pronounced at finer (e.g., subnational) spatial scales. Crop yield potential and actual performance during the best years is increasing in almost all cases—hence the nearly universal upward trends in crop yield across the country and world—but these will eventually reach an upper bound imposed by soil properties, weather, intrinsic limits on the efficiency of crop-plant biological processes, and availability and capture of sunlight, which is the ultimate driver of, and limitation on, plant growth and crop yield (Amthor, 2010; Rattalino Edreira et al., 2020).That upper bound has yet to be reached for major U.S. crops, and an important, but unanswered, question relates to the timing of its eventual arrival, which could differ significantly for different crops and even for the same crop in different locales.

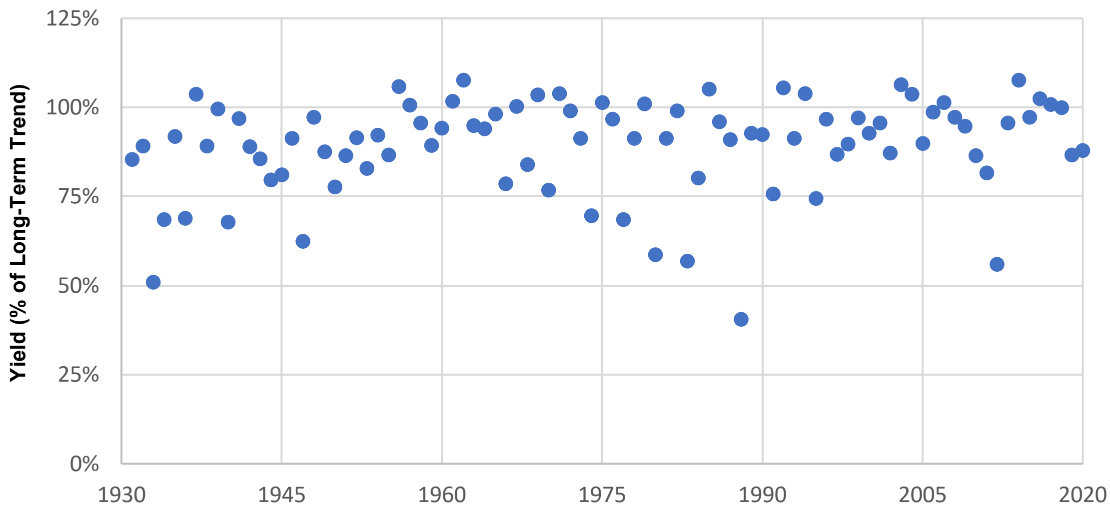

Figure 2. Corn yield as percentage of long-term yield trend in McLean County, Illinois, the U.S. county producing the most corn in recent years. Here the long-term yield trend (1931–2020) is modeled to reflect yield with generally favorable weather, in this case corresponding to about 90% of the best yields attained over time. The seven years with yield more than 25% below that trend since 1960 were 1974, 1977, 1980, 1983, 1988, 1995, and 2012, most of which were associated with poor weather at the regional scale, often drought, as mentioned in the text.

Crop Area and Production Trends

Crop *production*, as contrasted with yield, is the product of yield multiplied by area harvested. It is production, rather than yield *per se*, that most directly supports local and national economies and food security. Production can be increased through increased area of a crop (fraction of land available) or increased yield on existing acres, or a combination of both.

An important distinction exists between area of a crop planted at the beginning of any growing season and the area that is eventually harvested at the end of the season. Again, weather is often a critical factor. A crop planted in the spring can be damaged by weather (e.g., drought, flood, freezing, heat wave, hail, and/or severe wind), disease, or insect pests at any time during its life cycle. If the damage is serious enough, and harvestable yield is greatly reduced in any given field or portion of a field—perhaps to zero for a complete crop failure—that area may be left unharvested. Reported yield values are typically based on harvested area, but not all planted area is harvested. The difference between planted and harvested area can be economically important because costs of crop establishment are associated with planted area, and planted area reflects an expectation of revenue or economic return. The fraction of planted crop that is harvested is usually quite large; for example, only about 1.1% of soybean[1] planted in

[1] Area of corn planted for grain is not reported by USDA National Agricultural Statistics Service. Rather, reported planted corn area is for both grain and silage corn. Area of corn harvested for grain is reported, but the ratio of harvested/planted area for grain corn cannot be estimated from USDA National Agricultural Statistics Service data.

Illinois in 1988 was left unharvested (USDA National Agricultural Statistics Service) despite the significant drought that year. The fraction was higher during the flood year 1993, with about 3.2% and 3.5% of planted soybean unharvested in Illinois and Iowa, respectively. Although the fraction of planted area abandoned since about 1950 has been small, prior to that time bad weather often resulted in abandonment of a large fraction of planted acres (Hurt, 1981).

For the period 1950–2019, U.S. national area of harvested soybean increased by a factor of eight and corn area increased marginally. During the same period wheat area declined by nearly 50%, and cotton area declined by over 50% (Figure 3) due to several socioeconomic and other factors. As a result, total production increased for corn, cotton, and wheat mainly due to increased yield whereas soybean production increased mainly due to greater area of crop planted and harvested. A year-over-year change in harvested area of one crop can be negatively related to change in another. An example was 2007 when a large gain in corn area was balanced by a decrease in soybean area as farmers favored corn over soybean due to market conditions. Reduced area of both corn and soybean harvested in 1983, however, resulted from drought-caused prevented planting and failures in both crops. Indeed, harvested areas of cotton and wheat were also reduced in 1983 (Figure 3).

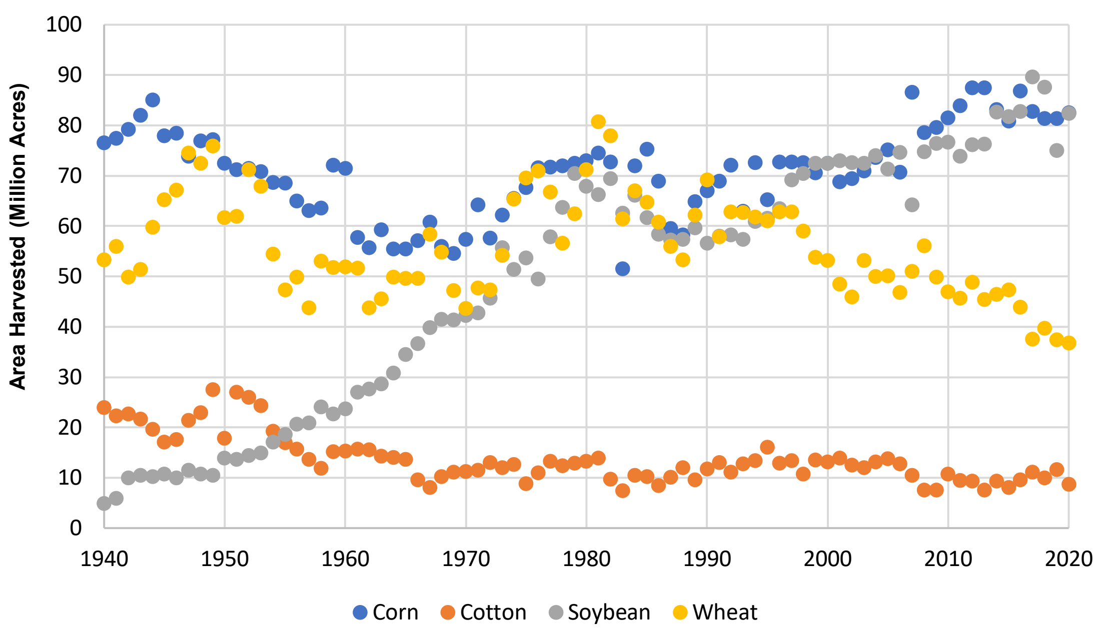

Figure 3. National area harvested of the four major U.S. row crops, 1940–2020. (Source: USDA National Agricultural Statistics Service)

As indicated by data in Figure 1 and Figure 3, national corn production has increased since 1940 mainly because of increasing yield rather than increasing area of crop harvested. The initiation of production gains being driven by yield gains might be pegged to the 1930s when hybrid seed corn became available across the Corn Belt. And as impressive as the production gains since the 1930s were, bad years were still quite bad (Figure 4). Examples are 1934, 1936, 1974, 1983, 1988, 1993, and 2012, with all of these except 1974 and 1993 associated with large-scale drought, including the Dust Bowl drought in 1934 and 1936. The main causes of low production in 1974 and 1993 were a wet spring (and early frost) and flood, respectively. Hence, all these examples of national corn production shortfalls relative to the general upward trend in production were due at least to a significant degree to extremes in rain, often coupled with temperature anomalies. As one further example, but from before the onset of rapid corn yield gains, the large proportional drop in corn production in 1901—which had the smallest national average corn yield for any year since 1866, when modern records began—coincided with extreme weather across the Corn Belt. Relative to the period 1895-2020, 1901 had the second highest (only to 1936) Corn Belt average July temperature and near-record Corn Belt July drought index (Palmer Z-index).[2]

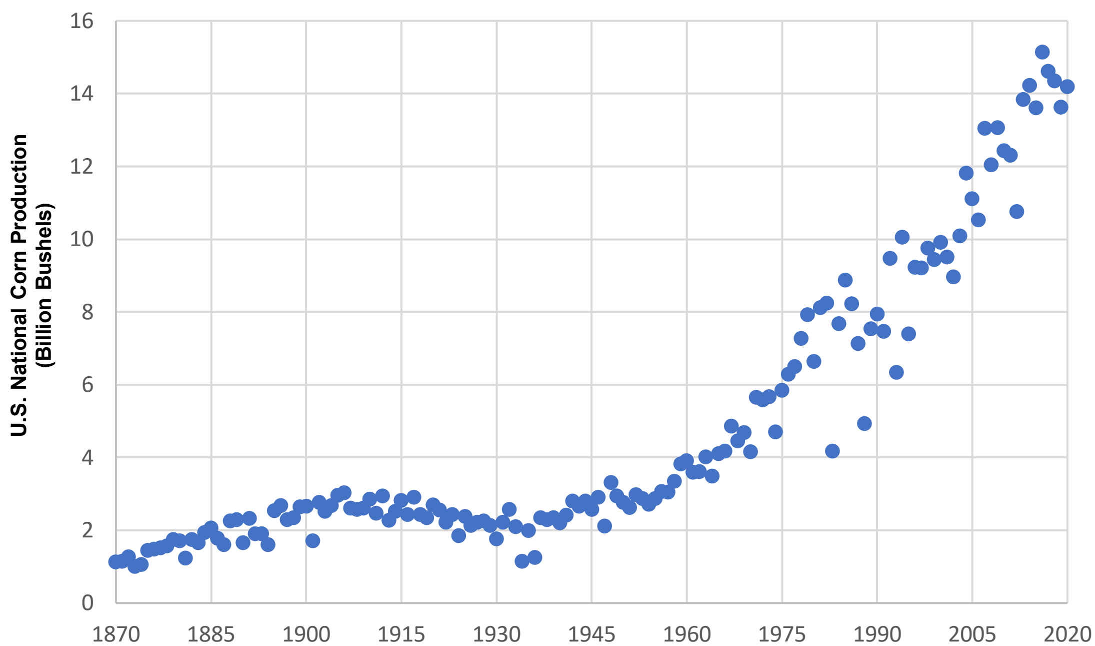

Figure 4. National corn production, 1870–2020 (Source: USDA National Agricultural Statistics Service). Area of U.S. corn reached an all-time maximum of 111 million acres in 1917, with yield during the average-to-good years stable over the period from 1870 through to 1940. As such, the broad increasing-then-decreasing pattern of production prior to 1940 was due to the increasing-then-decreasing area of corn. Beginning in the late 1930s, following the development and then acceptance of hybrid corn, and with the end of the Dust Bowl period, national corn yield began a more or less steady increase over time that continued through to at least 2016 (Figure 1), and likely through to today and into the future. The early acceptance of hybrid corn began in the center of the current Corn Belt (Iowa) in the late 1920s (Ryan & Gross, 1950) and spread outward to the rest of the country over a period of more than 20 years (Griliches, 1957).

[2] Data from https://www.ncdc.noaa.gov/cag/statewide/time-series. In this case, the Corn Belt is defined by NOAA, and differs slightly from the 13-state region used herein.

Both crop yield and the area of crop harvested contribute to total production, and fractional losses of total production resulting from poor weather during a growing season can, and generally do, exceed the fractional loss of yield. This was the case for the national corn production drop of 49% during 1983 (relative to 1982; Figure 4), which resulted from the combination of yield on harvested acres falling 28% and with area harvested being down 29%, both mostly as a consequence of widespread drought with the loss in area associated with both prevented planting and failure of planted crops. Losses of both yield and area of corn harvested were also extensive due to the exceptional drought and high-temperature stresses of the Dust Bowl years 1934 and 1936. Relative to 1932, which was a productive year, area of corn planted was down 11% and 10% in 1934 and 1936, respectively. More importantly, area harvested was down 37% and 30%, respectively, and yield on the harvested acres was reduced 29% and 30%, respectively. As a result, national corn production was down 56% and 51% in 1934 and 1936, relative to 1932. A 50% loss of corn production today, due to any cause, could correspond to a financial loss at the farm gate of USD 25–30 billion. The follow-on, cumulative losses throughout the food supply chain would be larger, perhaps by a considerable amount.

Dust Bowl crop losses were due to a combination of extremely unfavorable weather and poor land stewardship (Hurt, 1981), and although land stewardship has greatly improved since then, the prospect of such catastrophic crop loss due to future extreme weather, possibly associated with ongoing climate change, remains a cause for concern. After all, the Dust Bowl drought occurred prior to the onset of significant contemporary climate change, and our recent modeling of Midwestern corn yield forced by 1936 summer weather indicated losses much greater than those realized in 1988 (Hunt et al., 2020).

Climate Change as an Emerging Concern

As these and other statistics indicate, past climate variability (i.e., weather extremes) significantly impacted U.S. crop production, with corn seeing frequent large setbacks. Moreover, there is strong scientific consensus that future climate change may pose additional critical threats to future crops via both extreme events and changes to mean weather variable values (reviewed by Pritchard & Amthor, 2005; Walthall et al., 2012; Nelson et al., 2013; Porter et al., 2014; Urban et al., 2015; Hsiang et al., 2017; Zhao et al., 2017; Hatfield et al., 2018; Crane-Droesch et al., 2019).

Several estimates of effects of warming and associated climate change on corn yield have been derived, using a range of methodologies and being applicable to different geographies. For Wisconsin corn and soybean, yield reductions of 13% and 16% for each °C summer warming was proposed by Kucharik & Serbin (2008) based on historical yield and weather data analysis. In a modeling study, based on historical relationships between corn yield and weather, aggregate corn yield across the Midwest declined about 9% per °C warming (for warming of about 2°C), although a tiny fraction of area in the northern portion of the region was forecast to see warming-induced yield gains (Urban et al., 2012), perhaps through elimination of some low-temperature limitations on crop growth in the cooler north. For 19 corn models used to simulate crop responses to warming at Ames, Iowa, relative to the historical average for the period 1980-2010 and with warming applied uniformly to each historical day, the 25th and 75th percentile yield reductions were 4.8% and 6.6% per °C warming, respectively (Bassu et al., 2014). Damage functions developed by Hsiang et al. (2017) produced an average U.S. corn yield reduction of about 20% for a 2°C increase in global mean surface temperature. Global average corn yield reduction of 7.4% per °C global mean warming was estimated from a combination of four modeling and data analysis methods, with a greater than 10% yield reduction per °C global warming in the United States (Zhao et al., 2017). The previous modeling studies in general did not account for possible adaptations to future climate change, either in crop genetics or management practices used by growers. Instead, they were designed to isolate effects of climate variability and change *per se* on crop yield.

In addition to projections of corn yield decline resulting from climate change, it is also proposed that yield variability could increase (i.e., yield stability could decrease) with warming and drying (e.g., Urban et al., 2015).

Some of the yield reduction expected from future warming might be mitigated by increased rainfall, were it to simultaneously occur. For example, it was estimated that a 50 mm *increase* in summer rainfall in Wisconsin could stimulate yield by 5-10% (Kucharik & Serbin, 2008).

The ongoing increase in atmospheric CO_2 concentration, a main driver of global warming, will stimulate future crop growth and yield, especially in C3 crops. That stimulation is not, however, expected to fully offset potential negative effects on yield of significant warming nor to mitigate effects of extremes in weather (Pritchard & Amthor, 2005; Porter et al., 2014). For C4 crops, including corn, future increases in atmospheric CO_2 concentration *per se* may have limited effects on growth and yield, except perhaps in the face of drought, during which elevated CO_2 can stimulate corn yield (Leakey et al., 2006).

Study Goal and Approach

The goal was to quantify yield responses of corn—the United States' most valuable crop—to climate change in the 13-state U.S. Corn Belt (Figure 5). To do this, two model (numerical) simulation experiments were conducted using the process-based AIR Crop Growth and Yield Model (Appendix A). The first experiment (i.e., the *historical-weather experiment*) quantified effects of observed, historical weather in the period 1974–2019, including any actual climate change, on the Corn Belt's corn yield. The second experiment (i.e., the *climate change scenario experiment*) simulated corn yield responses to climate change scenarios during the period 1991–2055 as simulated (projected) by four leading general circulation models (GCMs). In both experiments the weather variables input to the crop model were daily total precipitation (liquid equivalent) and daily minimum (T_{min}) and maximum (T_{max}) air temperatures.

Both the historical weather and climate change scenario experiments were conducted on a 0.1° × 0.1° latitude/longitude grid, which is equivalent to map grid cells of about 6.9 miles south-to-north (latitudinal) × about 5.1 miles west-to-east (longitudinal) in the center of the Corn Belt (about 42°N latitude). The USDA Cropland Data Layer (USDA, 2020b) was averaged over the period 2015–2019 to estimate the fraction of each grid cell recently covered by corn (rainfed and irrigated combined).

The crop model isolated effects of climate/weather per se on yield by holding crop genetics and management practices constant at our view of their state circa 2019 over the full simulation period of 1974–2055. This is an approach commonly applied in other studies with the objective of understanding climate change effects. By doing so, the simulated year-to-year variation in corn yield was uninfluenced by the technologically based factors responsible for the marked positive historical yield trends illustrated in Figure 1. The exception was planting date windows, which tracked historical changes over the period 1974–2019; during that period, planting dates tended to become earlier, presumably in response to warmer winters and earlier springtime warmup over that period. Planting date windows for 2020–2055 were set to 2019 values. All comparisons of historical yields to modeled yields were done with linearly detrended historical yields, normalized to the trend yield value for 2019. All crop growth and yield simulations were separately conducted for rainfed and irrigated corn to assess effects of climate change on yield under those distinct water-management practices.

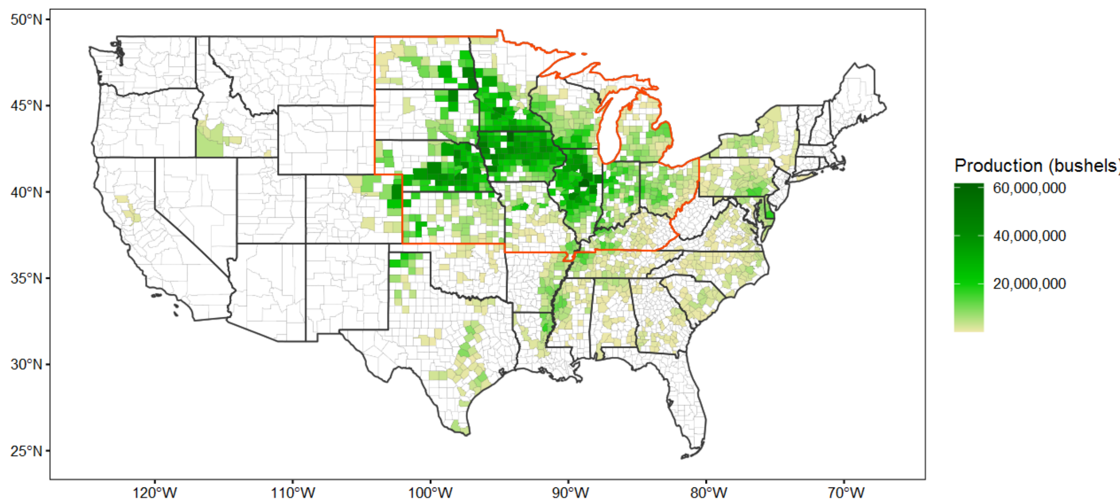

Figure 5. U.S. corn grain production by county during 2019 (USDA National Agricultural Statistics Service). The 13-state Corn Belt study region, enclosed in the red line, is composed of Iowa, Illinois, Indiana, Kansas, Kentucky, Michigan, Minnesota, Missouri, North Dakota, Nebraska, Ohio, South Dakota, and Wisconsin. The Corn Belt accounted for 87% of U.S. corn grain production in 2019 and nearly 30% of global corn production in recent years. The four states Iowa, Illinois, Nebraska, and Minnesota produced 55% of U.S. corn grain in 2019.

Crop model weather inputs in the historical-weather experiment

Weather data used as input to the crop model for the historical-weather experiment (1974–2019) were derived from daily precipitation total (accumulated to 12Z UTC) on a 0.25° × 0.25° latitude/longitude grid (Chen et al., 2008; NOAA Climate Prediction Center, 2021a) and daily T_{min} and T_{max} on a 0.50 × 0.50° latitude/longitude grid (Janowiak et al., 1999; NOAA Climate Prediction Center, 2021b). These data, which were processed and made available by the NOAA Climate Prediction Center (CPC), were resampled from the CPC-distributed database resolutions to the 0.1° × 0.1° experimental grid. Historical annual global mean atmospheric CO_2 concentration, obtained from measurements at Mauna Loa Observatory,[3] Hawaii, were also input to the crop model.

Crop model weather inputs in the climate-change-scenario experiment

For the 1991–2055 climate-change-scenario experiment, weather data input to the crop model was based on climate projections from four GCMs (ACCESS1-0, CCSM4, GFDL-CM3, and HadGEM2-CC) participating in the Coupled Model Intercomparison Project

[3] https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html

Phase 5 (CMIP5) (Taylor et al., 2012). The CCSM and GFDL models were included because of their fundamental importance to the U.S. climate change modeling community, the HadGEM2 model was included because of its high regard within the international climate modeling community, and the ACCESS model was included as an example of a model developed by teams predominantly interested in a geography far removed from the U.S. Corn Belt (i.e., Australia). In CMIP5, the GCMs were forced with historical atmospheric greenhouse gas concentration data through 2005 and the Representative Concentration Pathway (RCP) 8.5 atmospheric greenhouse gas concentration trajectories after 2005 (Moss et al., 2010; Riahi et al., 2011).

Gridded (CONUS 1/16°) daily minimum and maximum air temperatures and daily precipitation totals derived from the GCMs were obtained from LOCA CMIP5 projections (Pierce et al., 2014, 2015), including the historical period. Those weather data were assigned to each 0.1° × 0.1° latitude/longitude experimental grid cell from the nearest LOCA CMIP5 grid cell. Global annual average atmospheric CO_2 concentration values were also input to the crop model. These were based on direct measurements at the Mauna Loa Observatory, Hawaii, through the year 2019 and the RCP 8.5 atmospheric greenhouse gas concentration trajectory (Meinshausen et al., 2011) for the period 2020-2055.

Based on the RCP 8.5 atmospheric greenhouse gas concentration trajectories, the four GCMs provided a range of climate change projections across the Corn Belt over the period 1991–2055 (Figure 6). The GFDL model projected increased summer rainfall while the other models projected reduced rainfall in nearly all states, with the greatest reduction in all states but North Dakota seen for the ACCESS model. Both T_{min} and T_{max} increased for all states with all GCMs, with T_{max} increasing significantly more than T_{min} for the ACCESS model.

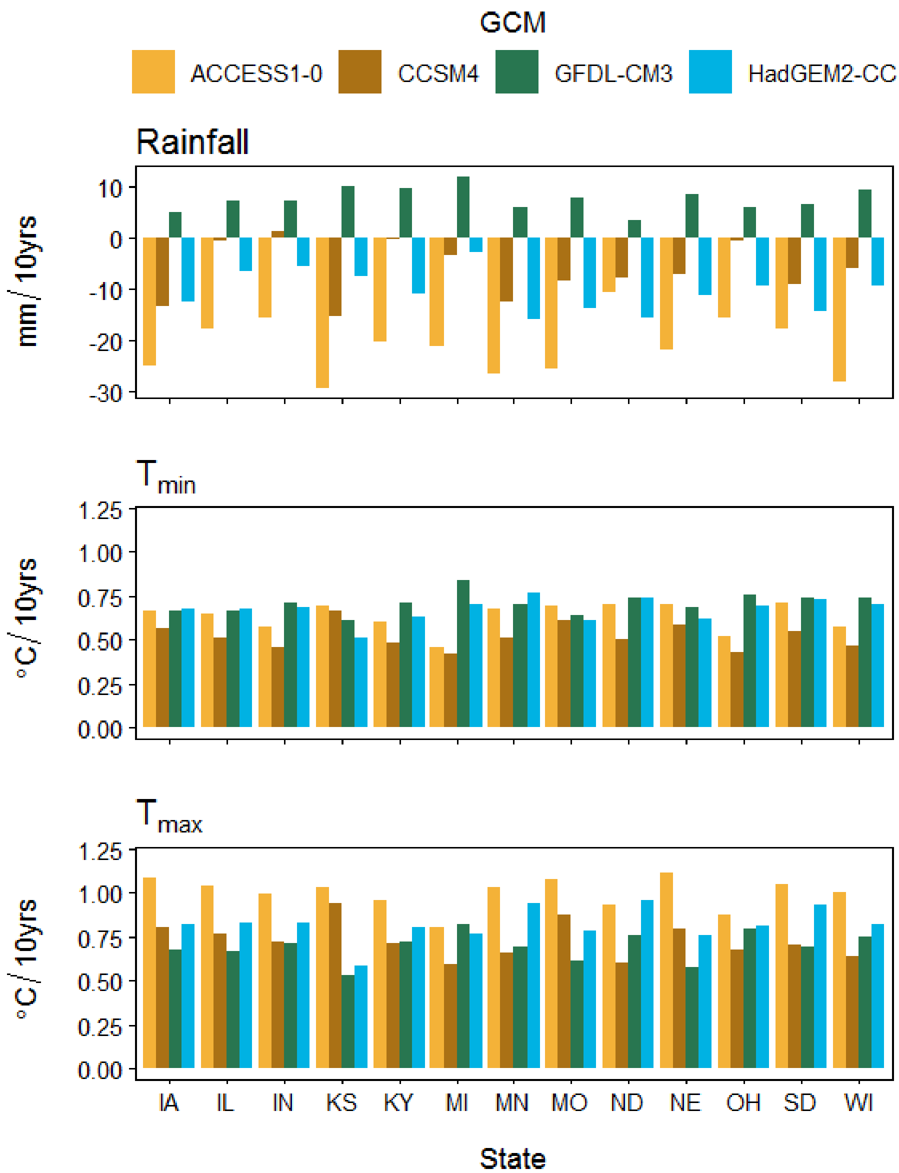

Figure 6. Average rates of change of summer (June-August) total rainfall (top panel; mm per decade), summer daily average T_{min} (middle panel; °C per decade), and summer daily average T_{max} (bottom panel; °C per decade) projected by each of the four general circulation models (GCMs) over the climate-change-scenario experimental period (1991–2055) for each of the 13 Corn Belt states. The GCMs were forced with historical (1991–2005) and RCP 8.5 (2006–2055) atmospheric greenhouse gas concentration data.

In this study, the RCP 8.5 (rather 2.6, 4.5, or 6.0) atmospheric greenhouse gas concentration trajectory scenario was chosen to explore a *business-as-usual* scenario, but it is not meant to be interpreted as an *outcome-is-likely* one. "Business as usual" means that this scenario assumes there are no climate change policies in place and is thus a baseline, or reference, view. Importantly, the RCP 8.5 scenario is not an outlier. A recent analysis found that RCP 8.5 is in close agreement with historical emissions and that it is the best match of the four RCPs “out to midcentury under current and stated [national energy] policies” (Schwalm et al., 2020). There are other reasons for not discounting RCP 8.5. While some assumptions underlying this scenario include significant growth in the use of coal (a circumstance that looks increasingly unlikely), other assumptions can be combined to produce a similar—or even worse—outcome, such as the thawing of high-latitude permafrost, which might release large amounts of methane, a potent greenhouse gas, into the atmosphere. On balance, RCP 8.5 remains a plausible upper bound and a useful analytical reference point.

Crop Yield Responses to Climate Change

Corn Yield Responses to Historical Weather, 1974–2019

Observed County-Average Corn Yield and Acreage Harvested in Recent Years

Detrended county average actual corn yields in the period 2010–2019 were highest in the four states producing the most U.S. corn: Nebraska, Iowa, Minnesota, and Illinois. Perhaps as expected, actual yields were highest in the center of the Corn Belt and declined toward the edges of the 13-state region, especially in the west (Figure 7).

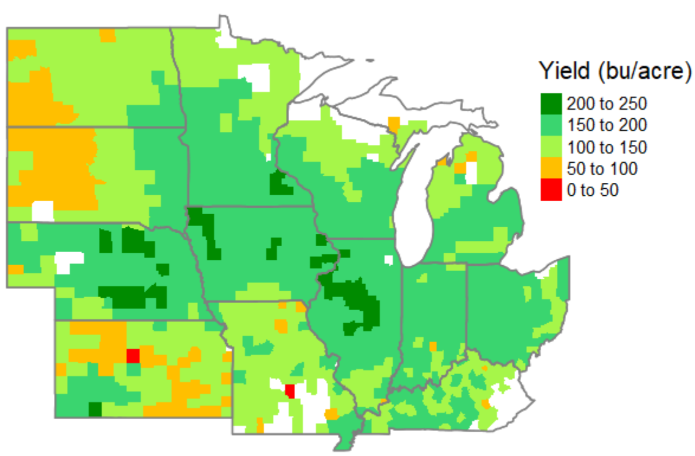

Figure 7. Detrended (to 2019 linear trendline values) average actual corn yield (bushels per acre) in each county in the Corn Belt during the period 2010-2019 reported by USDA National Agricultural Statistics Service. Lack of data for a county is shown by white, indicating little or no corn grown or harvested in a county in the past decade.

Counties in Nebraska, Iowa, Minnesota, and Illinois also account for some of the largest acreages of harvested corn, but several counties in eastern North Dakota and South Dakota also had high harvested-corn acreages in recent years (Figure 8, left). The only significant Corn Belt acreages of irrigated corn in recent years were in Nebraska and Kansas (Figure 8, right), which is consistent with a combination of relatively low summer rainfall and access to the Ogallala Aquifer in parts of those states. This is reflective of the fact that U.S. corn acreage is strongly dominated by rainfed crops. It might be expected *a priori* that any future reduction in summer rainfall or increase in summer daytime temperature that increased "atmospheric demand" for water evaporation, might each have a greater, and probably more negative, effect on rainfed corn relative to irrigated corn due to proportionally greater water stress in the rainfed crops.

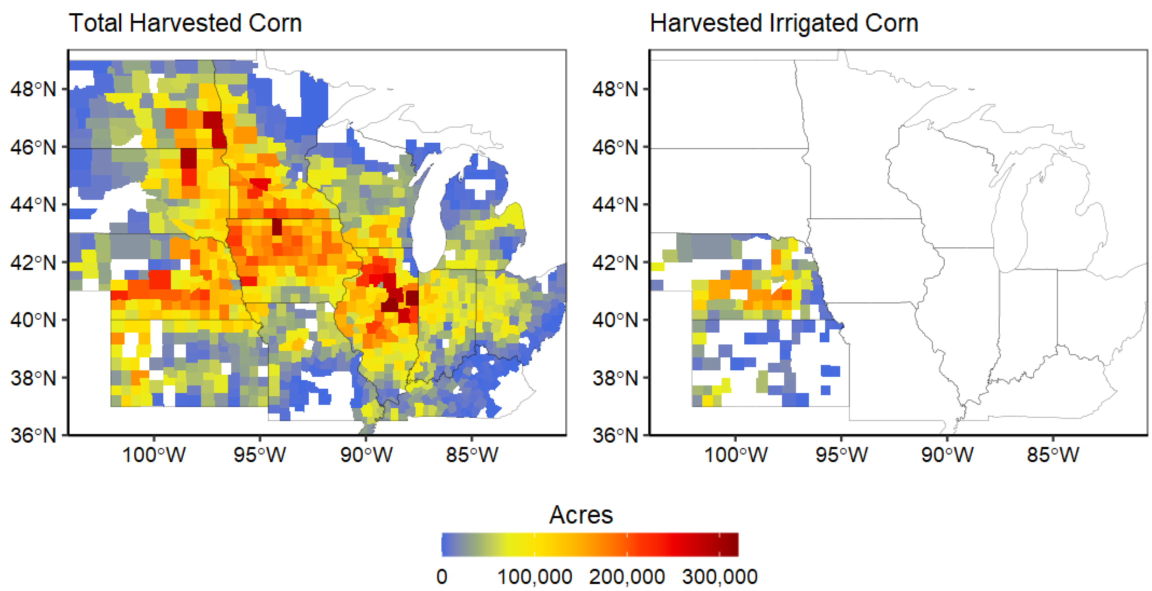

Figure 8. Average area of total (i.e., rainfed + irrigated) corn harvested (left) and average area of irrigated corn harvested (right) in each Corn Belt county during the period 2016–2019 (Source: USDA National Agricultural Statistics Service)

Modeled County-Average Corn Yield, 1974–2019

In the historical-weather experiment, climate change over the period 1974-2019 were *beneficial* to model corn yield across most of the Corn Belt. This was especially the case for most of the states producing most of the current U.S. corn crop.

One specific measure of corn response to climate change in the historical-weather experiment was a comparison of average yield in the first (1974–1983) and last (2010–2019) decades of the experiment. In that comparison, modeled decadal-average *rainfed*-corn yield increased across much of the Corn Belt, with the change in weather pushing more counties into higher-yield bins in most states, including near the western (dry) edge of the Corn Belt (Figure 9, bottom panels). Each of the first and last decades included a significant drought: during 1983 in the first decade and 2012 in the last decade.

Yield of modeled *irrigated* corn generally increased in the northwest quadrant of the Corn Belt but declined in parts of the southeast quadrant (Figure 9, top panels) between the 1974-1983 and 2010-2019 decades. This result may indicate a northwestward movement of weather most favorable for irrigated corn over the period 1974–2019. Most germane to the location of actual irrigated corn (i.e., Nebraska and Kansas) was the increase in yield in many Nebraska counties in the 2010–2019 decade relative to the 1974-1983 decade (Figure 9, top panels).

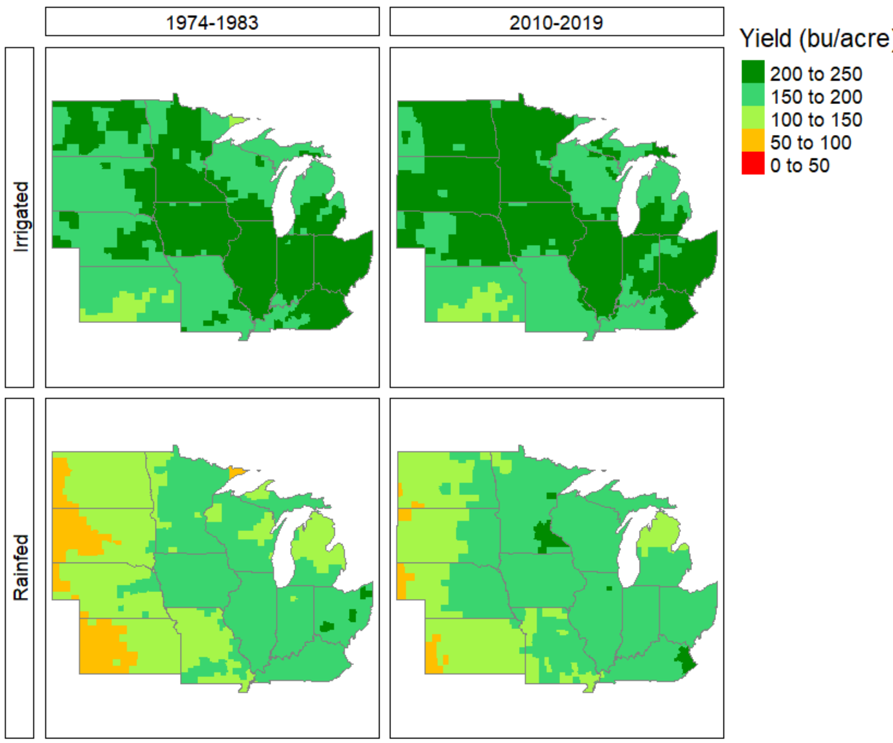

Figure 9. Average simulated corn yield (bushels per acre) during the decades 1974-1983 (left) and 2010-2019 (right) with crop genetics and other technological factors at circa 2019 values. Irrigated crops are in top panels, rainfed crops are in bottom panels. Note: even though the model experiment planted a corn crop in each 0.1 × 0.1° grid cell, the low model yield during 1974-1983 in Cook County in the northeast corner of Minnesota is insignificance because actual corn is not grown there (see Figure 8).

Modeled State-Average Yield Trends, 1974–2019

In the historical-weather experiment, simulated state-average yield of rainfed corn increased over the period 1974–2019 in all Corn Belt states but Ohio (Figure 10, red lines). Modeled state-average rainfed-corn yield increases were largest in South Dakota, Nebraska, North Dakota, Kansas, Minnesota, Iowa, and Missouri—essentially the western half of the Corn Belt—with rates of yield increase from nearly 0.4 to about 0.8 bushels per acre each year (Figure 11), or roughly 15–35 bushels per acre over the 46-year numerical experiment for those states.

Positive yield responses of modeled irrigated corn to climate change during the period 1974-2019 were more modest and mixed than for rainfed corn. Only seven of the 13 Corn Belt states experienced state-average modeled irrigated-corn yield increases over the experimental period (Figures 10, 11), albeit this included Nebraska and Kansas, the two states currently growing the large majority of irrigated Corn Belt corn (Figure 8, right map).

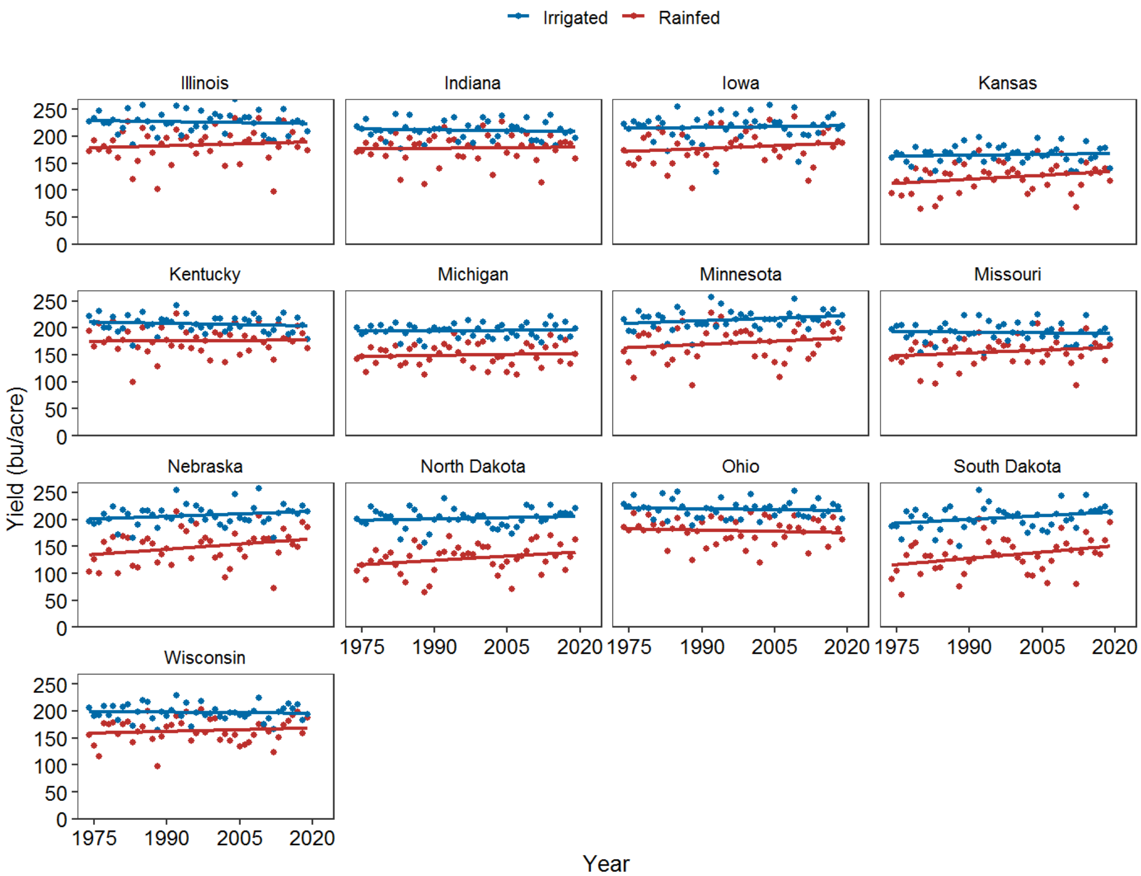

Figure 10. State average simulated yield (bushels per acre) in the historical-weather experiment for rainfed (red) and irrigated (blue) corn. Lines are linear regressions fitted to the data, which have positive slopes for rainfed corn in all states except Ohio. Rates of yield change (i.e., slopes of the regression lines) are summarized in Figure 11.

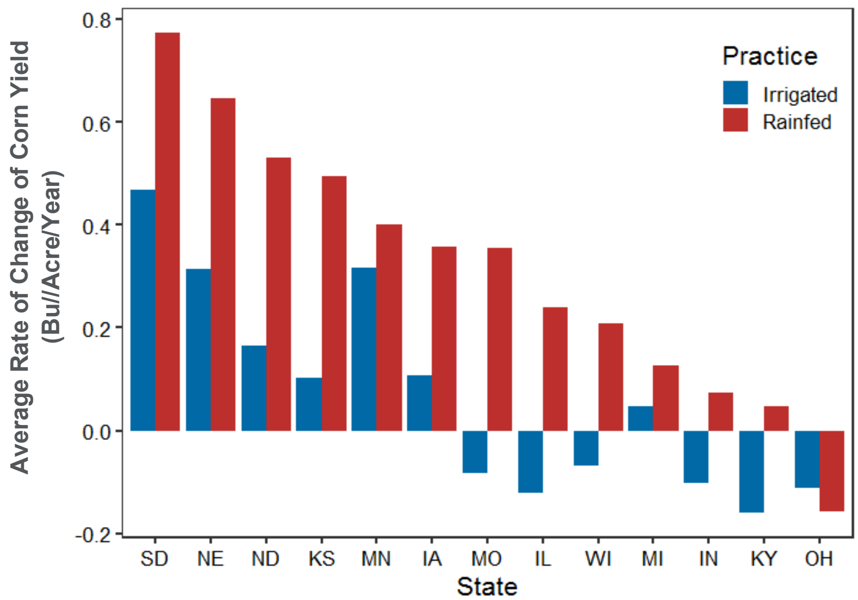

Figure 11. Average rate of change of simulated corn yield for each state over the period 1974–2019 in the historical-weather experiment in bushels per acre per year, with positive values indicating improving yield during the study period. Crop genetics and other technological factors were held constant across the study period so that modeled yield changes were due solely to changes in climate/weather.

Why Would Corn Belt Climate Change from 1974 to 2019 Benefit Corn Yield?

Earlier Spring Warmup and Planting Date

In prior research, the earlier planting dates for corn allowed with earlier spring warmup in the Corn Belt between 1979 and 2005—a consequence of past winter/spring warming—in combination with the use of hybrids with longer growing seasons (i.e., larger growing degree day [GDD] requirements to reach maturity), was proposed as a mechanism responsible for a significant fraction of the observed positive yield trend for corn (see, e.g., Figure 1) during that period (Kucharik, 2008). In our numerical historical-weather experiment, corn GDD requirement to reach maturity was held constant, but planting *did occur earlier* as time progressed since 1974 in correspondence with the observed earlier springtime warmup. This earlier planting both in historical experience and in the model, which can be considered an adaptive response by farmers to earlier spring warmup, may alter the calendar timing of crop anthesis (flowering). This is of potential importance because corn may be most susceptible to high-temperature stress around the time of anthesis and therefore if earlier planting causes anthesis to occur earlier in the summer—specifically, prior to the period of highest and potentially most damaging daytime maximum temperature—yield may be enhanced for that reason. In addition, a larger GDD requirement to reach maturity imposed by altered crop genetics over the historical period can allow the crop to grow over a longer calendar duration and therefore increase yield simply because the crop is growing for a longer time. The latter possibility will have applied to historical (actual) crops in the Corn Belt but was not applicable to the modeled crop.

Summer Weather

The June–August (summer) period accounts for the core of the growth period of corn across the 13-state Corn Belt study region and changes in actual summer weather since 1974 could have favored higher yields. Across most of the Corn Belt during 1974–2019, *summer* area-weighted (i) rainfall total increased 7.0 mm per decade, (ii) daily average T_{min} increased 0.21°C per decade, and (iii) daily average T_{max} *decreased* 0.16°C per decade. The Corn Belt–wide change in rainfall was a balance between increases in 10 states and decreases in the three others (Michigan, Minnesota, and Ohio) (Appendix B, Table B2). The largest state-level increases in summer rainfall were in Kansas, North Dakota, Nebraska, South Dakota, and Missouri, which are all in the western, typically drier part of the Corn Belt. To the extent that summer rainfall limits corn yield, which it often does (e.g., Thompson, 1986), increased summer rainfall would be expected to enhance yield, perhaps especially for rainfed crops. This view is generally consistent with model results indicating increased yield in states with increased summer rainfall (compare Table B2 [Appendix B] with Figure 11).

All Corn Belt states had increases in summer T_{min} with the largest increases in the eastern part of the study region (Michigan and Ohio). At the same time, a widespread *decrease* in Corn Belt summer T_{max} was driven by decreases in 11 of the 13 states, with T_{max} increases seen only in Kentucky and Ohio (those increases being only 0.01° and 0.08°C per decade, respectively) (Appendix B, Table B2). The largest declines in summer T_{max} were in the western portion of the Corn Belt, in this case South Dakota, North Dakota, Iowa, and Minnesota, which partially overlapped with the states experiencing the largest increases in summer rainfall. While increases in rainfall generally will have reduced modeled water stress by increasing water supply, especially in rainfed crops, reduced daytime T_{max} also will tend to reduce water stress by reducing water consumption—because lower T_{max}s will reduce evaporative demand of the atmosphere—and therefore conserving soil moisture. In addition, reduced summer T_{max} would tend to reduce high-temperature stress. Consistent with these potentially beneficial effects of reduced T_{max} on corn yield, especially for rainfed locations, modeled yield of rainfed corn in the states with the most significant declines in summer T_{max} (i.e., the Dakotas, Nebraska, Kansas, Minnesota, and Iowa) increased from nearly 0.4 to as much as about 0.8 bushels per acre per year (on average) in the historical-weather experiment (Figures 10, 11). That is, states with stable or declining summer T_{max} experienced the largest increases in modeled yield over the 1974–2019 experimental period. Ohio was the only state with a decline in simulated rainfed-corn yield during the 1974–2019 period and coincidentally had the greatest decline in summer rainfall and greatest increases in summer T_{min} and T_{max}. In both Ohio and Kentucky, which were the only states without a declining trend in summer T_{max}, and which had relatively large increases in the summer T_{min} trend, simulated yield of *irrigated* corn declined.

Although the 13-state area-weighted average decline in summer average T_{max} of about 0.7°C during the period 1974-2019, which we derived from the CPC data, contrasts with some national and global trends in *summer warming*, it is consistent with earlier reports of a summer warming hole in the Midwestern United States (Partridge et al., 2018). This observed Midwestern summer warming hole, which extends into autumn, apparently is associated with a warming hole in the Southeastern United States during winter and spring (Vose et al., 2017; Partridge et al., 2018). The causes of this summer Midwestern warming hole remain uncertain, but may be the result of a combination of factors, including but perhaps not limited to: anthropogenic aerosol emissions and resulting changes in cloud cover (Yu et al., 2014; Banerjee et al., 2017); multidecadal climate variability associated with climate indices over the Atlantic and Pacific Oceans (Meehl et al., 2012; Kumar et al., 2013) that are perhaps related to a mid 20th century jet stream shift (Weaver, 2013; Partridge et al., 2018); and intensification of cropping systems in the Midwest (Mueller et al., 2015, 2017; Alter et al., 2018; Nikiel & Eltahir, 2019). These presumed main drivers of the U.S. warming hole vary by season, geographic region, and historical time periods during the past circa 65 years (Mascioli et al., 2016) and except for any contributions from anthropogenic aerosol emissions and agricultural intensification, drivers of the warming hole may arise (or have arisen) from internal climate system variability rather than human actions.

Nonetheless, human intensification of cropping systems is obvious across the Corn Belt and this might be expected to increase the seasonal duration and magnitude of daytime evaporative land-surface cooling (latent heat exchange) through increased evapotranspiration resulting from dense crop canopies, and this is true even for rainfed crops at least to the extent that soil moisture is available in the cropped root zone (Basso et al.,2021). For irrigated crops that replace native vegetation, which are not extensive over most of the Corn Belt, a direct increase in evaporative cooling is expected (Nocco et al., 2019) and this would probably have a greater dampening effect on T_{max} than T_{min} because evaporative cooling is greatest during the warmer part of the day. But whatever the underlying mechanism(s) of the summer Midwestern warming hole, the observed cooling of summer T_{max} in combination with increased summer rainfall over much of the Corn Belt during the period 1974–2019 probably contributed positively to the historical increases in yield during that period.

Reduced Crop Stresses Since 1974

As discussed earlier, and for rainfed crops in particular, a major cause of Corn Belt corn yield loss in recent decades was drought. And for both rainfed and irrigated crops, flooding during any part of the growing season can reduce yield. Similarly, both rainfed and irrigated crops can suffer yield loss associated with extremes in temperature. Moreover, even a modest warming during the growing season can cause yield shortfall. That is, an increase in temperature, even a small one, when averaged over the growing season will cause the crop to reach maturity more quickly because the crop’s developmental rate increases with temperature and the GDD requirement for crop maturation is reached earlier. That shortening of the period of crop growth, and especially the duration of the grain growth period in the later part of the season, typically will result in lower yield.

Overall losses of yield in actual crops will often be caused by combinations of these factors, and in many important instances by interactions between moisture availability and temperature. Because the AIR crop model accommodates all these yield-damaging factors, and their interactions as mediated through changes in crop water balance and crop developmental status, the model is an effective tool for quantitative analysis of crop responses to observed weather and can be used to differentiate effects of different environmental factors on final yield (Appendix C).

In particular, the crop model indicates that as a result of climate change during the period 1974-2019 water stress was reduced because of a combination of increased summer rainfall and reduced summer T_{max}. High-temperature stress, especially damage to reproductive structures that give rise to grain production, was directly reduced because of declining T_{max}, and indirectly reduced through greater daytime evaporative cooling of the crop because of the greater transpiration facilitated by greater soil moisture due to greater rainfall. And frost/freeze damage was reduced because of increasing T_{min}.

Increased corn yield, as simulated by the AIR crop model, associated with climate change during the historical 1974-2019 period is *not* opposed to the often-cited reduction in corn yield with warming because the observed summer average T_{max} *declined*, rather than increased, over most of the Corn Belt during that period. Both the (a) warming hole and (b) adaptation to earlier spring weather through planting date adjustments (and, in the case of actual compared to modeled crops, the use of longer-duration corn genotypes) will have contributed to recent climate change–related benefits to the Corn Belt's corn yields. While the AIR model fully accounted for the summer warming hole and accounted for planting date adjustments, it otherwise intentionally held crop genetics and management practices constant to isolate effects of climate change *per se* on yield.

Previous Assessments of Corn Yield Response to Recent Climate Change

A previous, coarser-resolution analysis of crop yield trends in relation to changes in weather during the period 1980-2008 indicated that U.S. corn yield was slightly positively affected by temperature change and negatively affected by change in rainfall, with a net negative effect of climate change on national yield (Lobell et al., 2011). For the period 1990–2019, a crop model driven by historical weather simulated a 1.7% decrease in yield in the central portion of the Corn Belt, whereas weather over the period 1960–2019 caused modeled yield to fall less than 0.5% (Basso et al., 2021). These net negative effects of past climate change over recent 29-, 30-, and 60-year periods on yield is counter to the present beneficial effects on corn yield for the major U.S. corn-producing states over the period 1974–2019.

But other modeling experiments and statistical analyses of relationships between the Corn Belt's corn yield and weather during recent decades did indicate net gains in yield due to earlier planting dates and/or summer climate trends during recent decades. For example, 28% of observed corn yield gain in the Corn Belt (excluding North Dakota) over the period 1981–2017 was attributed, based on county-scale yield-weather modeling, to "weather shifts since 1981" (Butler et al., 2018) (see Figure 1 for national corn yield changes since 1940). In a process-based crop-model study, average corn yields were about 5–10% less than the actual historical average across the Corn Belt through the year 2011 under a counterfactual climate scenario lacking the observed historical warming hole, indicative of a positive effect of the warming hole on yield (Partridge et al., 2019). And a statistical analysis of relationships between weather and corn yield indicated a positive yield response to Corn Belt weather in the United States during the period 2004–2008 relative to climate in the period 1944–1973 (Ray et al., 2019). The present study indicating beneficial effects of historical climate change on corn yield in the U.S. Corn Belt covers a more recent period, up through 2019, than the previous assessments cited above.

Corn Yield Responses to GCM-Simulated Climate Change, 1991–2055

In nearly all cases, RCP 8.5 GCM-projected weather during the decade 2046–2055 caused modeled corn yield to fall across the 13-state Corn Belt relative to GCM-simulated weather during the decade 1991–2000 (yield ratio less than 1.0 in Figure 12).

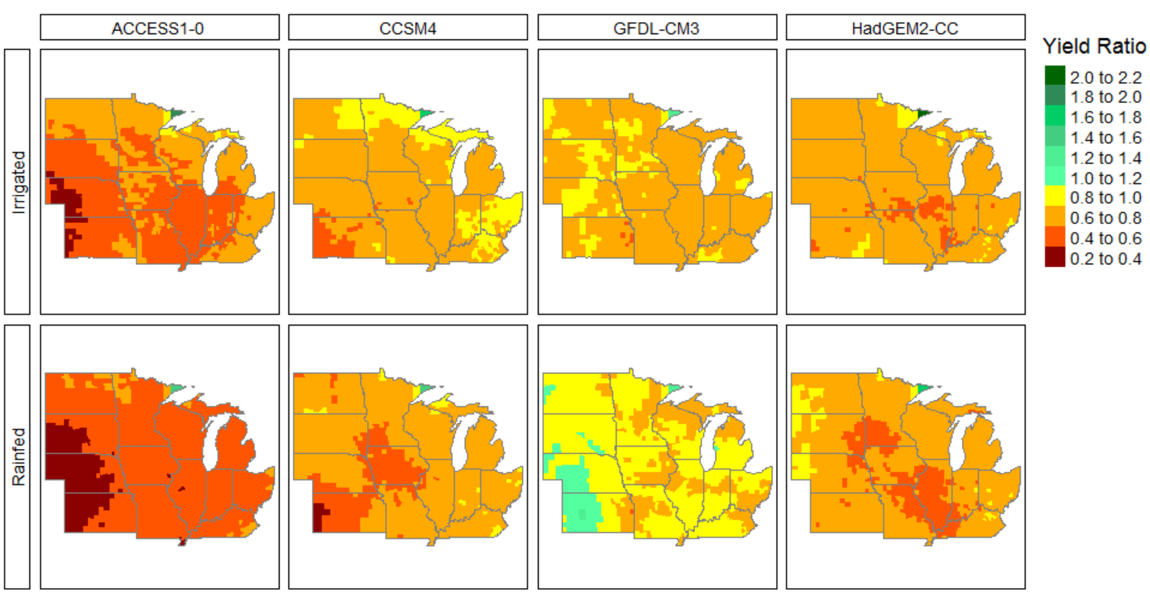

Figure 12. County-average corn yield during the period 2046-2055 relative to the period 1991-2000 (yield ratio = average yield during 2046-2055 / average yield during 1991-2000). The top row is irrigated crops and bottom row is rainfed crops. Columns represent crop model yield simulations

using daily weather downscaled from each of the four GCMs (forced with RCP 8.5 atmospheric greenhouse gas concentration trajectories) as input. (Note: the high yield ratio in Cook County in the northeast corner of Minnesota is of limited significance because grain corn is not grown there in actuality even though the model established a crop in every county.)

Over the 1991-2055 experimental period, modeled corn yield declined for both rainfed and irrigated crops in every county in the 13 Corn Belt states (except Cook County in the northeast corner of Minnesota, which does not normally have an actual corn crop) based on weather derived from the ACCESS1-0 GCM, which had the largest proportional decline in summer precipitation and largest increase in summer T_{max} over the period 1991-2055 (Figure 6). The drop in rainfed-corn yield was 40–60% across nearly all the Corn Belt while the drop in irrigated-corn yield was 20–60% over nearly all the Corn Belt (Figure 12).

Using weather derived from the GFDL-CM3 GCM, which projected increased summer rainfall in combination with considerable warming during the period 1991-2055, rainfed-corn yield increased in a few counties in North Dakota and South Dakota and in the western halves of Nebraska and Kansas, but yield of irrigated corn fell in every county (except Cook County, Minnesota) (Figure 12). For most of the rest of the Corn Belt, yield fell 0–20% for rainfed corn and 20–40% for irrigated corn. This implies that the increase in summer rainfall projected by the GFDL model did sometimes, but not usually, compensate for the yield reductions caused by concomitant warming.

Modeled yield response to weather derived from the CCSM4 and HadGEM2-CC GCMs was intermediate between responses to weather derived from the ACCESS and GFDL GCMs for most Corn Belt counties. For rainfed crops, yield reductions were at least 20%, and often more than 40%, in the core of the Corn Belt (i.e., Illinois, Iowa, southern Minnesota, and eastern Nebraska) during the decade 2046-2055 relative to the decade 1991-2000 (Figure 12).

Thus in general, the reduction in average yield during the decade 2046-2055, relative to the decade 1991-2000, was greater in rainfed corn than for irrigated corn, with the exception of the GFDL-CM3-based climate-change scenario, which included increased summer rainfall in the later decade, and even yield increases in some of the western (mostly southwestern) portions of the Corn Belt.

Yield Drop per °C Warming

When averaged over the entire study area and over the four GCMs, yield of modeled rainfed corn fell 7.1% per °C summer average daily warming across the Corn Belt. For irrigated corn, modeled yield declined 6.5% per °C summer warming averaged across the Corn Belt. These values are within the range of previously published estimates (referenced earlier), though they were obtained in an independent manner and at a finer spatial resolution and/or wider model domain than in those previous studies.

Across the four GCMs, modeled rainfed-corn yield reduction per °C Corn Belt warming ranged from 3.0% (GFDL GCM) to 9.9% (ACCESS GCM) (Figure 13). This reflects considerable uncertainty in projections of rainfed-corn yield response to future climate change. For irrigated corn, which accounts for a small fraction of total Corn Belt corn production, variation in yield reduction per °C Corn Belt warming was considerably less, ranging from 6.0% (GFDL GCM) to 7.6% (ACCESS GCM). The smaller modeled corn yield drop per °C Corn Belt warming found for the GFDL GCM-derived climate change projection was almost certainly related to the increase in summer rainfall accompanying the projected warming over the period 1991-2055, with the other three GCMs projecting a reduction in rainfall coincident with the warming.

For each GCM climate-change scenario, there was variation in modeled corn yield reduction per °C warming between different states, with greater variation for rainfed than for irrigated crops. There was larger variation in modeled corn yield reduction per °C warming between different GCM climate-change scenarios within each state, again with larger variation for rainfed crops than irrigated crops (Figure 14). Nonetheless, the general qualitative differences between the four GCM-based climate-change scenarios were maintained across states, with yield reductions per °C warming being smallest with the GFDL-derived climate change projection in nearly all cases (Figure 14).

Overall, the four GCM-based climate change scenarios caused significant declines in decadal-scale average corn yield, but with significant uncertainty as indicated by differences between yield responses to weather derived from the different GCMs.

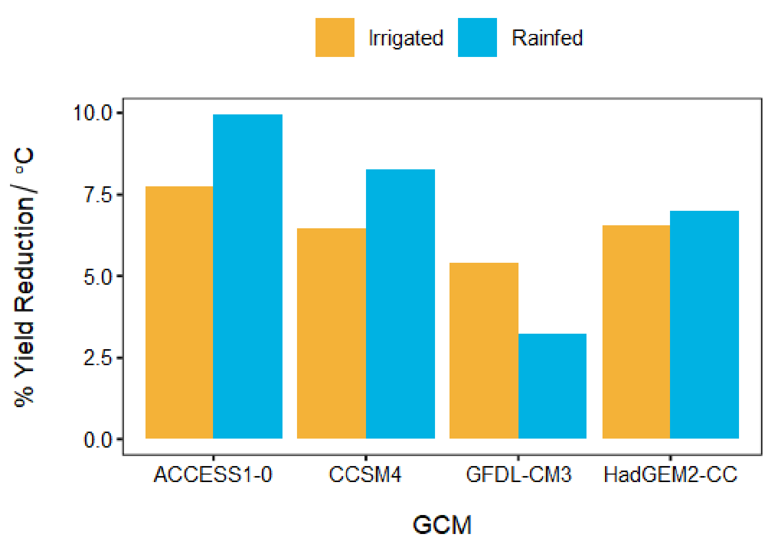

Figure 13. Average percentage yield reduction across the 13-state study area per °C average summer daily temperature increase over the period 1991-2055 for the corn yield simulations forced by climate projections from the four GCMs forced with RCP 8.5 data, which served as sources of daily weather data for the corn growth and yield model. Values are derived from area-weighted responses of corn in each 0.1° × 0.1° pixel.

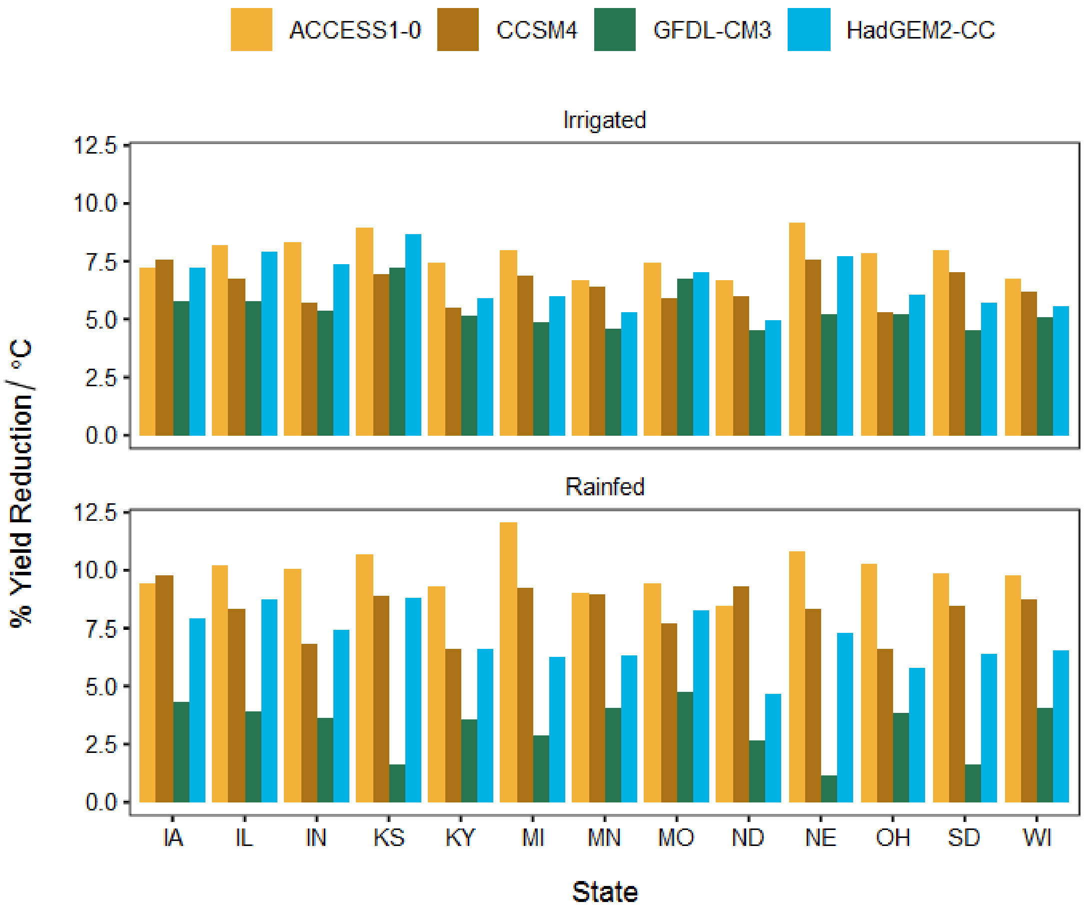

Figure 14. Percentage yield reduction per °C daily average summer warming (daily average temperature increase) over the period 1991-2055 for the state-average corn yield simulations forced by climate projections from the four GCMs forced with RCP 8.5 atmospheric greeenhouse gas concentration trajectory values, which served as sources of daily weather data for the corn growth and yield model.

Crop Yield Stability Responses to Climate Change

The ability of a crop to maintain consistent yield across different environments, including environments represented by interannual variation in weather, is a measure of yield stability. Yield stability from year to year supports economic stability including long-term planning by growers and financers. Any climate change–induced reduction in yield stability—i.e., any climate change–caused increase in interannual yield variation—could increase risk of economic loss during any given year as well as reduce reliability of supplies of food, livestock feed, and biofuels.

Coefficient of variation (CV) of corn yield during multi-year periods (i.e., standard deviation of yield divided by mean yield during the period) is one way to characterize yield stability and is what was measured in this study. Crops with greater frequency of large yield losses have larger CVs, and hence provide less reliable (or predictable) revenue streams from on-farm production of grain.

Corn Yield Stability Responses to Historical Weather, 1974–2019

In the historical-weather experiment, yield CV differed by region and was consistently greater for rainfed crops than for irrigated crops (Figures 15). This is generally as expected. Rainfed crop CV tended to be greater in the western half of the Corn Belt, where summer rainfall typically is lowest, and more variable, and where water stress is expected to be most significant in low-rainfall years.

During the first and last decades of the historical-weather experiment, 1974-1983 and 2010-2019, respectively, both the mean and variance of county-level corn yield CV were larger in rainfed relative to irrigated corn (Figure 16). Only rarely did yield CV of irrigated corn in any county exceed the CV of rainfed corn.

Across the 13-state Corn Belt, yield CV for the decade 2010-2019 relative to 1974-1983, i.e., the CV ratio (= CV for the decade 2010-2019 / CV for the decade 1974-1983), was 1.09 and 1.03 for irrigated and rainfed corn, respectively. This indicated a slight general reduction in yield stability over the 46-year (1974-2019) historical-weather experiment.

County-level CV ratio was greater than unity (reduced yield stability over time) in about half the study area, and in the center of the Corn Belt it was generally greater for irrigated than rainfed corn (Figure 17). While region-wide corn yield CV changed little over the historical-weather experimental period, because of limited climate change during the period, there did exist pockets of counties with significant CV changes (Figure 17).

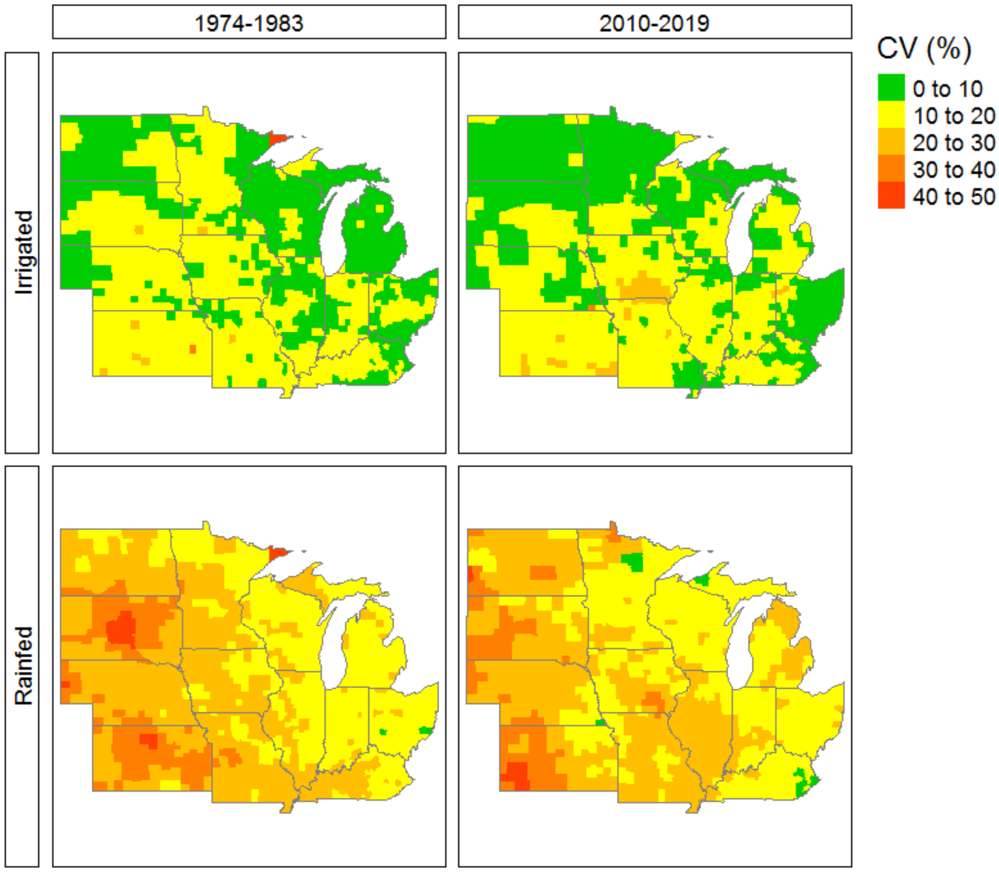

Figure 15. Coefficient of variation (CV, %) of corn yield for the decades 1974-1983 (left) and 2010-2019 (right) in the historical-weather experiment. Top panels are irrigated crops and bottom panels are rainfed crops. (Note: the high CV during 1974-1983 in Cook County in the northeast corner of Minnesota is of limited significance because actual grain corn is not grown there even though a modeled crop was established in every county.)

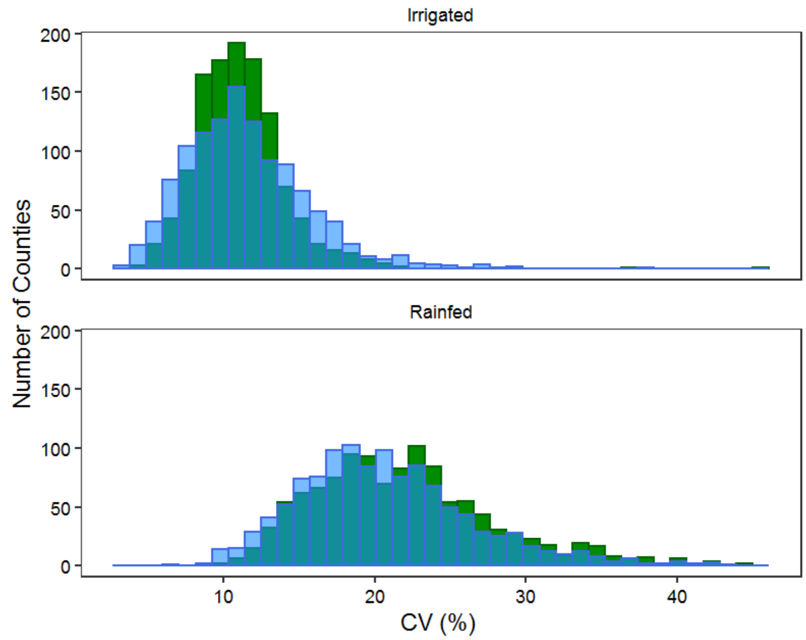

Figure 16. Distribution of coefficients of variation (CV, %) of annual county-average yields of irrigated (top) and rainfed (bottom) corn during the decades 1974-1983 (green) and 2010-2019 (blue). Ten-year periods are used to reduce impact of single, possibly extreme, years on this measure of yield variation, for example, the droughts in 1983 and 2012 These are the first and last decades of the 1974–2019 period and are taken to represent effects of climate change over the historical-weather experimental period.

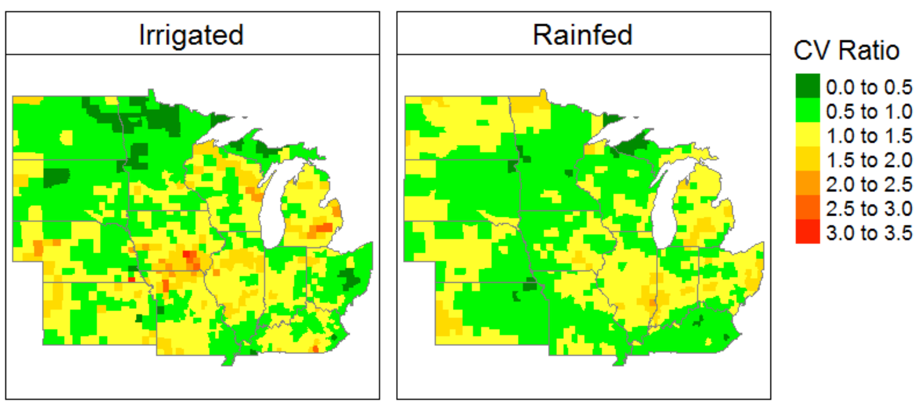

Figure 17. Ratio of coefficient of variation (CV) of corn yield between the decades 2010-2019 and 1974-1983 (i.e., CV ratio = CV for the decade 2010-2019 / CV for the decade 1974-1983) in the historical-weather experiment for irrigated (left) and rainfed (right) crops.

Corn Yield Stability Responses to Simulated Climate Change, 1991-2055

The climate-change-scenario experiment indicated a general, and sometimes large, increase in county-level corn yield CV during the decade 2046-2055 relative to the decade 1991-2000 (Figure 18). The largest relative change in county-level modeled CV, for both irrigated and rainfed crops, was associated with the ACCESS1-0 GCM, which was the GCM projecting the largest proportional decline in summer rainfall and largest increase in summer T_{max} over the study period. The smallest changes in county-level yield CV were associated with the GFDL-CM3 GCM climate-change scenario.

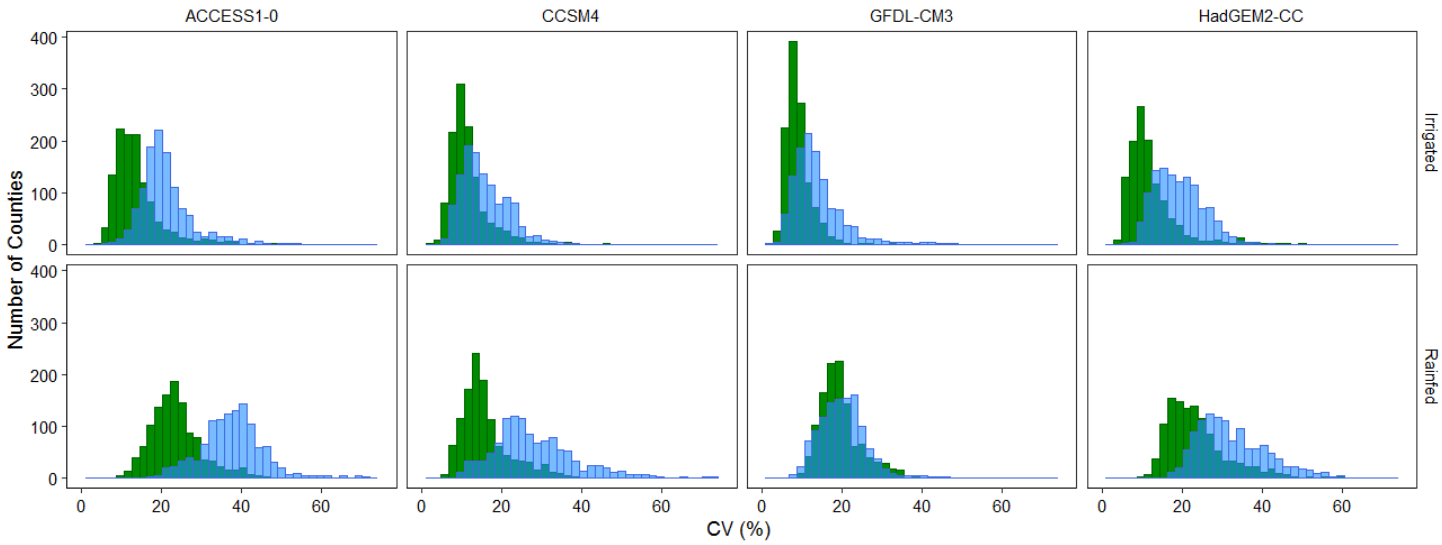

Figure 18. Frequency distribution of county-level corn yield coefficient of variation (CV) during the decade 1991-2000 (green) and the decade 2046-2055 (blue). Irrigated crops are shown in the top panels and rainfed crops in the bottom panels. Each column corresponds to a different climate change scenario derived from a different GCM forced with RCP 8.5 data. Those climate change scenarios were the bases for daily weather used as input to the crop model.

This important finding of generally increased CV—or stated differently, reduced yield stability—associated with projections of future climate change in the Corn Belt is consistent with earlier statistically based modeling studies of U.S. corn yield (Urban et al., 2012, 2015). Because, as discussed above, crop yield variation is skewed toward lower yields, increases in CV imply more frequent and/or greater magnitude of yield shortfalls in the future.

Modeled county-level changes in CV over the 1991-2055 study period were geographically diverse, with considerable variation between climate change scenarios derived from the different GCMs (Figure 19). The greatest increases in county-level yield CV tended to be in the southern half of the Corn Belt. Conversely, most of the counties with reduced yield CV were in the northern half of the Corn Belt, but in many cases those counties were only minor producers of corn in recent years. The GFDL-CM3-based climate change scenario resulted in the least number of counties experiencing CV ratio increases and the greatest number of counties with decreased CV ratio (i.e., increased yield stability).

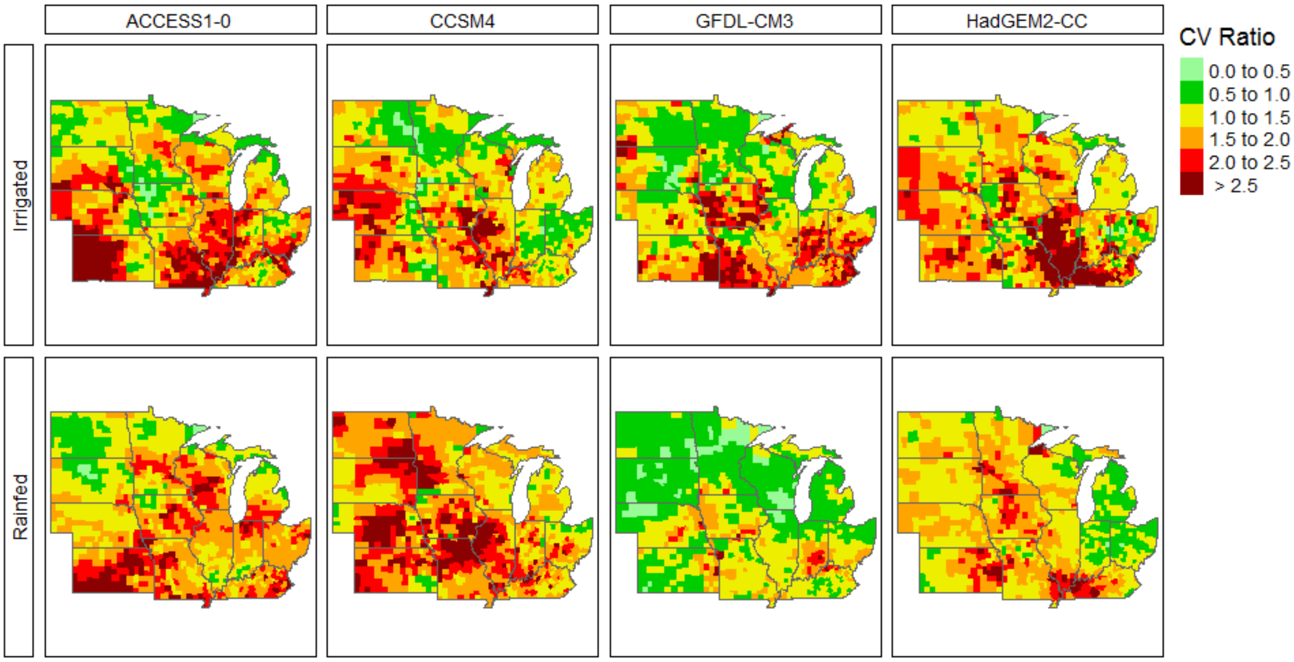

Figure 19. County-average corn yield coefficient of variation (CV) during the period 2046-2055 relative to the period 1991-2000 (CV ratio = CV during 2046-2055 / CV during 1991-2000). Top panels are for irrigated crops, bottom panels for rainfed crops. Each column represents a different GCM forced with RCP 8.5 data, which served as sources of daily weather data for the corn growth and yield model.

Reliability of Weather Data and Climate Projections

The usefulness of model-based analyses of crop responses to weather or climate change depends in part on accuracy, or representativeness, of the weather or climate data used as input to the crop model. (The other key factor is realism of the crop model.) Our view is that the NOAA CPC gridded daily precipitation, T_{min}, and T_{max} data are of high fidelity, and that our mapping of those data onto the 0.1° × 0.1° grid in the historical-weather experiment was of high quality. Therefore, we judge the weather data input to the crop model in the historical-weather experiment to be reliable and not a significant source of uncertainty in the results.

Conversely, the simulations of crop responses to future climate variability and change did entail significant uncertainty associated with the weather data ingested by the crop model. Output from the four different GCMs used as input to the crop model resulted in different future corn yield and yield stability projections. For example, the average yield loss for modeled rainfed corn of 7.1% per °C warming across the 13-state Corn Belt was an average of crop model simulations based on weather scenarios derived from four

GCMs, with variation in average yield reduction due to the different GCMs ranging from 3.0 to 9.9% per °C warming, which is notably more than a three-fold difference from the smallest yield loss to the largest (Figure 13). Moreover, modeled corn yield response to each climate change scenario (i.e., each GCM) varied between states, and between counties within each state (Figure 14). Overall, this implies considerable uncertainty about future Corn Belt corn yield and yield stability *due to* uncertainty in future climate change associated with differences between these four GCMs.

Given the sometimes significant differences in the details of climate change projections between GCMs, with large percentage differences in magnitude and sometimes even the sign of a change in a key climate variable such as summer rainfall amount, along with a usual lack of a clearly “best” GCM, an ensemble modeling approach is often used in climate change studies (e.g., Knutti et al., 2010). Our use of four GCMs was not intended to provide a single best climate change scenario for the Corn Belt. Rather, we used output from four GCMs to obtain some insights into the range of climate change possibilities associated with the RCP 8.5 atmospheric greenhouse gas concentration trajectory scenario and the types and ranges of potential crop responses to that possible range of climate change.

We did observe two aspects of the climate simulations provided by the four GCMs used in this study that raise some concern about their reliability for climate change studies focused on crops *in the Corn Belt* during the next few decades. (1) All four of the GCMs simulated significantly greater summer warming than observed over most of the Corn Belt during the past 10–20 years (Appendix B, Figure B4).. (2) While field measurements indicate a decline (contraction) in summer Corn Belt diel (daily 24-hour) temperature range, i.e., $T_{max} – T_{min}$, during recent decades, the GCMs did not reproduce such a climate characteristic. This indicates a too rapid increase in T_{max} relative to T_{min} in the GCMs. Both these discrepancies tend to exaggerate the frequency and magnitude of high-temperature stresses in the modeled crop. As such, these four CMIP5 GCMs, using the RCP 8.5 atmospheric greenhouse gas concentration trajectory scenario, may simulate a climate that is more stressful to corn (and other crops) *in the Corn Belt* than that of the actual recent and near-future climates. At the least, those CMIP5 GCMs may be forecasting summer Corn Belt warming several years ahead of reality. Our preliminary analysis indicates qualitatively similar results from the newer CMIP6 model runs.

Even though current and recent (CMIP5) GCMs contain imperfections and uncertainties, with those uncertainties varying between models, they are nonetheless the best scientific tools available to understand and forecast likely future changes in climate. And while CMIP5 models (and CMIP3 models before them) did not generally represent the warming hole well, Kumar et al. (2013) concluded that six of 19 CMIP5 models they studied showed “overall positive skill in simulating the [summer] warming hole–related features.” Those six included two of the GCMs used in this study: GFDL-CM3 and

HadGEM2-CC. Despite that, we did not find good agreement between those GCMs and observed summer Corn Belt T_{max} during the period 2000-2019 (Figure B4).

Looking forward, it is expected that post-CMIP5 GCMs may more reliably characterize the recent and possible future summer Corn Belt climate, including the warming hole and its future persistence or disappearance. Several mechanisms have been identified that may help improve GCM skill in this regard. For example, models with better skill in simulating the North Atlantic Oscillation appear more capable of reproducing features of the warming hole (Kumar et al., 2013), and improved land surface process representations might better account for any quantitatively important effects of intensified cropping on the warming hole. But in spite of likely improved understanding of the role of anthropogenic forcings on Corn Belt summertime climate change, including features of the warming hole, it may be important to recognize that internal climate variability on a regional scale could have played a large role in the history of the warming hole and perhaps will be key to its future fate (Kunkel et al., 2006; Mascioli et al., 2017). If that is true, many GCM simulations may be required to develop a probabilistic view of the future Corn Belt climate. In any case, an expected future improved GCM-based characterization of the U.S. Midwestern warming hole would (will) better position us to quantify both the timing and magnitude of future Corn Belt climate and resultant effects on Corn Belt crop yield, yield stability, and local and regional crop production. With this will come an improved view of potential consequences of future climate for agriculture, the downstream enterprises it supports, and the communities that depend on them.

Conclusions and Research Needs

This study used a unique combination of historical daily weather data, GCM projections of future climate, and a process-based model of crop responses to soil and weather applied at a high spatial resolution to quantify effects of past and future climate change across the U.S. Corn Belt on yield and yield stability of corn, the country's most valuable crop. Key results of this assessment include

- Changes in historically observed weather (climate trends) over most of the U.S. Corn Belt during the period 1974–2019 were beneficial to simulated corn yield when crop genetics and management practices (except planting date) were held constant at circa 2019 values. This was especially true for rainfed crops, which make up a large majority of current U.S. corn production. It was also the case for irrigated corn in Kansas and Nebraska, the two states currently with a significant area of irrigated corn. The beneficial effects on simulated yield of climate trends since 1974 were related at least in part to modest increases in summer (June–August) rainfall coupled with stable, or slightly declining, summer daily maximum temperatures across much of the Corn Belt. The stable or declining summer daily maximum temperatures are a key feature of the Midwestern summer warming hole apparent during the past ~65 years.

- Downscaled output from all four of the GCMs used in this study, as forced with the RCP 8.5 atmospheric greenhouse gas concentration trajectory scenario, indicated increases in summer daily minimum and maximum temperatures across the Corn Belt for the decade 2046–2055 relative to the decade 1991–2000. For three of the four GCMs there were generally greater increases in summer daily maximum temperatures relative to daily minimum temperatures. This is counter to recent observations of greater increases in minimum temperatures resulting in a decrease in the diel (daily 24-hour) temperature range (i.e., smaller differences between maximum and minimum temperatures in recent years). The fourth GCM (GFDL-CM3), however, did generally forecast reduced diel temperature range over time.

- Downscaled output from three of the four GCMs used (as forced by the RCP 8.5 scenario) indicated reduced rainfall for most of the Corn Belt for the decade 2046–2055 relative to the decade 1991–2000. This would indicate greater water stress in the future, especially for rainfed crops, should such a future develop. The fourth GCM (GFDL-CM3) projected increased rainfall over most of the Corn Belt, which might indicate the possibility of reduced water stress in the future.

- In the climate-change-scenario experiment, changes in weather (climate trends) over the U.S. Corn Belt derived from output of the four GCMs (as forced by the RCP 8.5 scenario) for the decade 2046–2055 relative to the decade 1991–2000 were detrimental to simulated corn yield when crop genetics and management practices were held constant at circa 2019 values. This was the case for downscaled weather outputs from all four of the GCMs used as inputs to the process-based crop model. Yield reductions occurred for both rainfed and irrigated crops at the state level for all 13 Corn Belt states for all four GCM climate scenarios. For output from three of the four GCMs, yield reductions caused by future climate were greater for rainfed, relative to irrigated, crops.

- Overall average simulated corn yield reductions for the GCM-based climate change scenarios between the decade 2046–2055 relative to the decade 1991–2000 was on the order of 6–7% per °C summer warming. The smallest declines in simulated corn yield between the decade 2046–2055 and the decade 1991–2000 were associated with downscaled output from the GFDL-CM3 GCM. This was related to (a) increases in summer rainfall projected by the GFDL-CM3 model, with the other three GCMs projecting reduced summer rainfall and (b) smaller increases in summer daily maximum temperatures projected by GFDL-CM3 GCM relative to the other three GCMs. In addition to reduced crop model yield, all four GCM-based climate change scenarios caused increased year-to-year variation in yield during the decade 2046-2055, an indicator of reduced yield stability in the future.

- Downscaled output from all four of the GCMs used in this study lacked a reproduction of the summer warming hole observed over much of the Corn Belt during the period 1974–2019. This has implications for the use of these (and other CMIP5) GCMs to study the possible time course of future Corn Belt climate change on the sub-decadal to decadal time scale since the GCMs have forecast greater, and in some cases significantly greater, warming than that observed through the year 2019. Specifically, future warming and changes in precipitation, if any, over much of the Corn Belt might be expected to occur more slowly than projected by the GCMs considered in this study.

As is the case for all studies of effects of projected future climates on the structure and functioning of crops and other terrestrial ecosystems, assumptions are made, and limitations are inevitable. For this study:

- Biases in downscaled output from the GCMs for the Corn Belt were evident for the period 1974-2019, including
  - A lack of simulation of the observed, quantitatively important Midwestern summer warming hole, and
  - A lack of simulation of the observed contraction of the summer diel temperature range, i.e., T_{max}–T_{min}.
- The only variables in the crop model as used in the climate-change-scenario experiment were weather and atmospheric CO_2 concentration, which therefore excluded a range of possible adaptation responses including, but not limited to
  - Development of improved, more stress-tolerant crop genotypes,
  - Changes in crop growing degree day requirements to reach maturity that might better fit future crops to a warmer climate, and
  - Changes in crop mixes, rotations, or replacement if corn becomes no longer suitable where it is now grown (the only crop simulated in this study was corn).

Several questions requiring further research can be posed, some of which can be addressed with further application of the AIR Crop Growth and Yield Model, or similar modeling approaches. These include:

- What are the key adaptation options for more resilient crop genotypes? For example, better drought tolerance within the confines of biophysics. This is not a new topic since drought is often the major factor limiting crop yield, and some promising options appear available, but what are the practical possibilities should the frequency or magnitude of future droughts rapidly increase?

- What are the most significant implications of the simulated increase in interannual variation in yield caused by future climate change for both food security and economics (profitability) of U.S. crop production?

- Can irrigation reduce/eliminate future effects of increased drought frequency or magnitude in major U.S. crop-growing regions? And if so, by how much and for how long (how many acre-years) can available irrigation water supplies persist given the fact that major U.S. aquifers are being drained to support crop irrigation—groundwater is the predominant source of irrigation water in the Corn Belt, but surface water is also used (Dieter et al., 2018)—and opportunities for refilling seem remote?

- Can a northern migration of the Corn Belt circumvent negative effects of future warming? Will rural communities be able to adapt to such a migration if it takes place? And will factors such as suitable soil and access to needed irrigation water to the north allow such migration?

- Will the past/current Midwestern warming hole "close" rapidly in the (near) future resulting in especially rapid future warming across the Corn Belt—more rapid than the background, global temperature increase—with increased summer daily maximum temperatures and heat wave frequency or magnitude causing significant additional damage (high-temperature stress) to corn and other crops?

- Are there temperature or soil moisture thresholds (tipping points) for crop damage that will be surpassed in the next few decades and that will lead to catastrophic crop failures over large areas?

- If the future climate is unconducive to corn production, will economically viable replacement crops be available? This may be studied by parameterizing crop models for alternative crops with different water- and high temperature–stress tolerances, growing degree day requirements to reach maturity, and/or transpiration-use efficiencies. It is important to note that corn may have a near maximal transpiration-use efficiency among likely crop candidates in the Corn Belt.

- Will, or how will, continuing advances in the fidelity of GCMs alter the view of likely effects of the future climate on crop yield and yield stability among different crops grow in different regions? Will future GCMs and/or other modeling approaches be able to significantly improve understanding of the causes, and future magnitude and time course, of the Midwestern summer warming hole?

- What policy responses to the possibly big impacts of climate change on U.S. agriculture could be attempted, how effective might they be, and in what time frame?

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Appendix A: AIR Crop Growth and Yield Model

The AIR Crop Growth and Yield Model was designed to simulate crop responses to daily weather (total precipitation, minimum air temperature, maximum air temperature, maximum wind speed) for applications in AIR's probabilistic agricultural risk modeling framework. It uses a process-based approach to simulate daily crop development (phenology) and growth (biomass accumulation) based on whole-plant developmental and physiological responses to temperature, rainfall, sunlight, and soil physical properties (texture). The model simulates wind damage (lodging) but that was not implemented for this study.

The crop model is a one-dimensional (point-based) model, generally implemented at points on a spatial grid, that links crop and soil water balances to biomass accumulation through transpiration-use efficiency (TUE) (de Wit, 1958; Tanner & Sinclair, 1983; Sinclair, 2018). In the model, TUE is a function of afternoon atmospheric vapor pressure deficit (VPD). That function is parametrized to produce realistic daily biomass accumulation even at very low VPD—i.e., humid air—and accounts for intrinsic differences in TUE between different crop types (e.g., TUE is greater for corn than for wheat). The model uses a daily time step and runs continuously—pre-season, in-season, and post-season—from the beginning to the end of a multiyear simulation period. The pre- and post-season simulations maintain a continuous time course of the vertical profile of soil moisture so that soil moisture at the time of planting is realistic (e.g., the crop season is *not* started with some arbitrary soil moisture profile). In this study the simulation periods were January 1, 1974, to December 31, 2019, for the historical-weather experiment and January 1, 1991, to December 31, 2055, for the climate-change-scenario experiment.

Static model inputs are (i) site latitude, which is used to calculate daily top-of-the-atmosphere solar irradiance that is used to estimate reference evapotranspiration, and (ii) vertical profile of sand and clay content in a horizontally layered soil extending to a maximum depth of 3 m. Soil texture determines modeled water holding properties (e.g., volumetric water content at air dry, permanent wilting point, and 'field capacity' values) and hydraulic conductivity of each horizontal layer based on models in Saxton & Rawls (2006).

For this study, the soil was divided into 5-cm thick layers with site-specific sand and clay volumetric content derived from the International Soil Reference and Information Centre (ISRIC) global gridded soil information database (Hengl et al., 2017) assigned to each horizontal layer (with silt fraction given by difference). The vertical profile of soil texture was assumed to be constant during the 1974–2019 and 1991–2055 experimental periods. Thus, any soil erosion, changes in bulk density caused by machinery traffic, and any changes to water holding capacity brought about by management practices (including reduced tillage) over time were ignored. This was done in part to focus the model results on climate change *per se*, with other time-dependent factors held constant at circa 2019 values.

Time-dependent model inputs for this study were daily minimum and maximum air temperatures (1.5 m height) and daily total precipitation (liquid water equivalent). Snow accumulation and melt are simulated where needed to account for seasonality of infiltration and runoff in higher latitudes. This is necessary to properly simulate soil moisture in the planting date window and during the early parts of the crop growth period.

In the U.S. implementation of the model, crop planting occurs within a predefined planting window for a county, with the specific date during each simulated year determined by air temperature, lack of snow cover, moisture in the top 0.15 m of soil, and rainfall on a potential planting date. Daily crop developmental rate, which begins the day of planting, is then based on thermal time (i.e., growing degree days) calculated from air temperature. Initiating the crops biological clock at the time of planting assumes imbibition begins almost immediately.

Daily crop and soil water balance simulation includes interception loss, throughfall and stemflow, runoff, transpiration, soil-surface evaporation, infiltration, vertical transport between soil layers based on water potential gradients, deep drainage out of the soil profile, and root water uptake from soil layers containing roots to support transpiration. Soil-surface evaporation and transpiration calculations follow an approach described by Allen et al. (1998), including a crop coefficient (K_{cb}) that is based on the crop's developmental stage and atmospheric CO_2 concentration. The value of K_{cb} represents the ratio of evapotranspiration possible from a crop relative to that from a healthy, well-watered reference crop under the same environmental conditions. Hence, K_{cb} generally increases (decreases) as the area of healthy leaves in the crop canopy increases (decreases) over the crop life cycle, including the loss of healthy leaf area under stress conditions and later in the life cycle during canopy senescence. When a corn crop has achieved high leaf area, K_{cb} typically will exceed unity.

The daily modeled transpiration is converted to daily net biomass production, which is broadly speaking the balance of photosynthetic gains and respiratory losses of carbon, through the TUE. Daily biomass production is accumulated throughout the crop growth period. It is halted when the crop reaches maturity as defined by date that total cumulative thermal time after planting reaches the total required for (associated with) crop maturity.

Seed production is the goal of growing corn for grain, and seed production (or harvested) per unit area of crop is the measure of crop yield. The fraction of final crop biomass that is composed of seeds is the *harvest index*, which is modeled as a function of the fraction of whole-season crop growth occurring after anthesis in combination with simulated seed set (see below). Final yield is obtained from harvest index and total biomass accumulation.

The model operates in either a *rainfed* or *irrigated* mode. To simulate an irrigation event, enough water is added to a specified depth of soil to bring that soil to a predetermined fraction of field capacity. The trigger for an irrigation is a specified volumetric water content in the surface soil layers set to prevent water stress. For this study, irrigation timing was determined based on soil moisture content, relative to field capacity, in the top 0.6 m of the soil. On dates when the integrated soil moisture content fell below 60% of field capacity, irrigation was simulated by adding enough water to the top 0.6 m of soil to bring it uniformly to 90% of field capacity.

Crop Responses to Environment

A range of abiotic stress factors that directly affect crop growth (biomass accumulation) and senescence are simulated, including vulnerability and damage functions for extremes of crop temperature (reviewed by Pritchard & Amthor, 2005; Sanchez et al., 2104; Schauberger et al., 2017) and soil moisture. Optimum temperature and soil moisture amount for growth are defined for each crop, with negative or positive departures from those optimums reducing TUE through physiological stress coefficients on rate of biomass accumulation. Effects of daytime temperature on daytime VPD also affect modeled TUE. Canopy senescence is accelerated by both high-temperature and low-soil-moisture stresses. In extreme cases, temperature or moisture stress may cause mortality.

When daily maximum air temperature exceeds a threshold value in the days just before, during, or after anthesis—i.e., the time of flowering and the fertilization of eggs by pollen resulting in embryos that grow into seeds—the model implements an hourly time-step temperature simulation for that day (adapted from Kimball & Bellamy, 1986). It does this to more precisely simulate the maximum temperatures, which are generally reached in the afternoon, when (i) damage to pollen and eggs, (ii) interference with pollination, and (iii) embryo mortality are greatest. That simulated damage (i)-(iii) is integrated by the model into seed set, which is the relative number of seeds produced per plant; the typical row-crop corn plant grows one ear, but that ear will have a different number and size of seeds depending on crop genotype and environmental conditions during the period of crop growth. This negative response to high-temperature extremes around the time of anthesis, which may be significantly more frequent or extensive with future climate change, is observed not only in maize, but for other grain crops as well (e.g., Ferris et al., 1998; Pritchard & Amthor, 2005).

Moisture content in the soil layers containing roots affects rates of crop biomass accumulation, root elongation (depth) growth, and canopy senescence. Soil saturation and/or extended retention of water on the soil surface can cause time-dependent, flood-related damage to the crop. Modeled feedbacks between transpiration amount and biomass production are mediated through leaf area expansion and senescence processes and through effects of soil moisture across the soil profile on root elongation (i.e., root depth growth and therefore access to deeper soil water). Conversely, limited soil moisture reduces transpiration through both direct limitations on water available to be extracted from the soil and through closure of stomatal pores in the crop's leaves through which the bulk of transpiration occurs. In the model, the transpirational (stomatal) response to low soil moisture is nonlinear. When transpiration is limited by soil moisture stress, crop canopy temperature increases, potentially to stressful degrees, and this is simulated by the model. Transpiration is completed halted when soil moisture content in soil layers containing roots reaches the permanent wilting point. Soil moisture stress also accelerates leaf senescence, so it affects K_{cb} in the model.

The model includes an inverse relationship between atmospheric CO_2 concentration and K_{cb} to represent stomatal closure caused by elevated levels of CO_2. The model does not account for any direct effects of CO_2 concentration on corn photosynthesis or growth. This is based on the assumption that the rate of corn photosynthesis is not significantly limited by availability of CO_2 in the present atmosphere, at least in the absence of drought, i.e., corn photosynthesis is said to be CO_2-saturated at present atmospheric CO_2 concentration (Leakey et al., 2006; but see Ghannoum et al., 2000; Franks et al., 2013).

Crop Model Parametrization and Validation

For this study, the model was parameterized for current (ca. 2019) crop genetics, farmer skill, and management practices to reflect current corn growth and yield potential. As such, the simulation experiments did not account for potential future adaptation to climate change or historical or future changes in corn yield potential. The study goal was to assess the likely response of current corn crops to past and future weather *per se* by holding crop genetics and management practices constant with only weather and atmospheric CO_2 concentration changing over time.

As the starting point for this study—following model parametrization—the crop model was compared to (validated with) county-level corn yield histories for all reporting U.S. counties over the period 1974–2019 (USDA National Agricultural Statistics Service [NASS]; https://quickstats.nass.usda.gov/), for both rainfed and irrigated crops. Modeled county average corn yield was calculated from yield each year in each 0.1 × 0.1° grid cell weighted by the area of corn in each grid cell as derived from the USDA Cropland Data Layer (USDA, 2020b) averaged over the period 2015–2019, and with each grid cell weighted by its (fractional) area within a county. In turn, the reported county average corn yields for all counties in the NASS database were linearly detrended with respect to the year 2019 to align historical yields with current crop genetics (yield potential). A comparison was then made between modeled yields and NASS historical yields, with values for the period 1974–2019 for the eight U.S. Corn Belt counties producing the most corn during the period 2000–2019 illustrated in Figure A1. Notable historical corn yield shortfalls occurred in many parts of the Corn Belt in 1983, 1988, 1993, and 2012, as mentioned in the main text, and were simulated by the crop model.

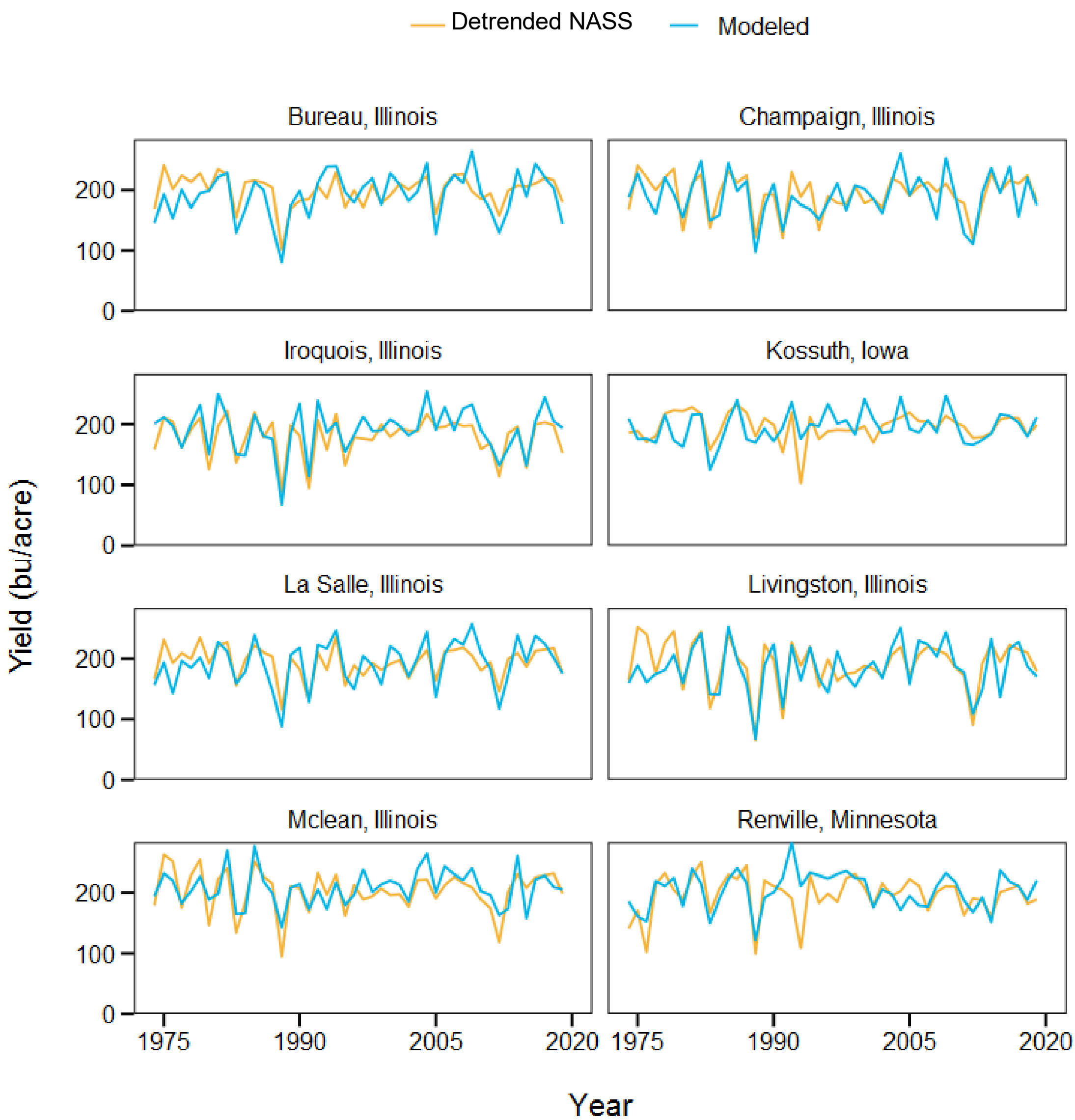

Figure A1. Modeled and detrended NASS yields (bushels per acre) over the period 1974–2019 for the eight U.S. counties producing the most corn during the last 20 years. Orange lines indicate NASS reported yield values detrended to the year 2019 and blue lines are simulations from the AIR Crop Growth and Yield Model parameterized for corn with 2019 crop genetics and management practices.

Detrended long-term average (1974–2019) corn yields for each county in the conterminous United States in the NASS database is mapped along with corresponding model simulations for the same period in Figure A2.

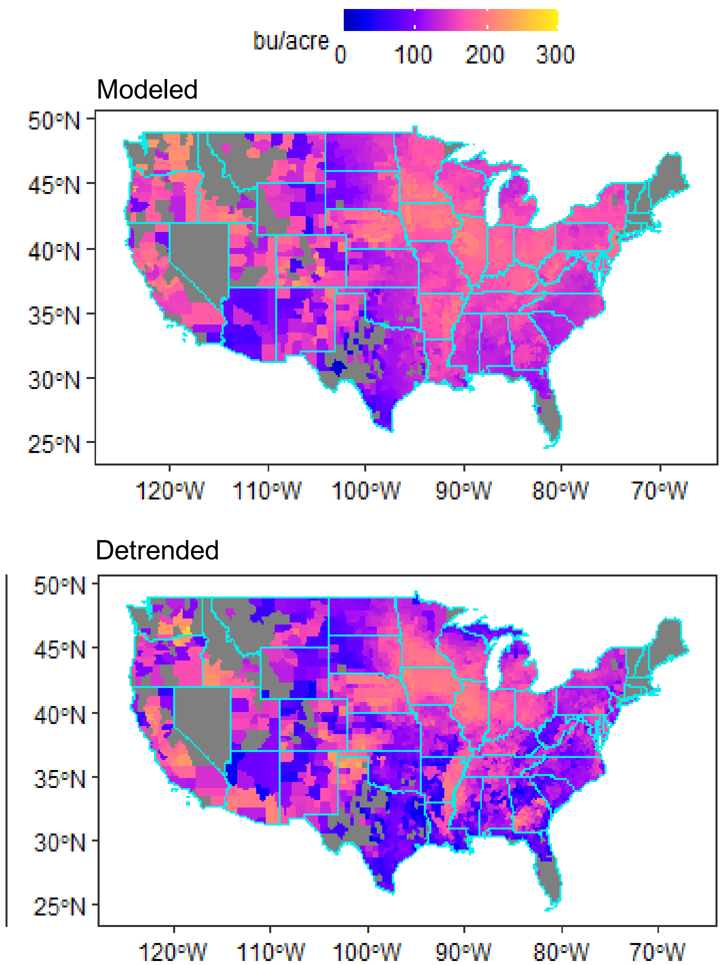

Figure A2. Modeled (top) and detrended NASS (bottom) long-term (1974–2019) average corn yield (bushels per acre) at the county scale over the conterminous United States. Reported yields were detrended relative to 2019. Grey counties denote no data in the NASS database, with model output excluded for those counties.

Root mean square error (RMSE; standard deviation of the modeled-reported residuals, or prediction errors) values for model yield simulations relative to detrended NASS data for each county with corn yields in the NASS database are shown in Figure A3. The areas with weaker model–NASS data agreement (larger RMSE) correspond in general to counties with sparse or incomplete historical yield time series, which will have the greatest uncertainty in actual yields because of relatively limited historical experience. Those same counties also correspond to limited production (yield × area harvested) and therefore of limited significance to U.S. national corn production.

The correspondence in interannual variation—amplitude of peaks and troughs, and timing of yield shortfalls—between modeled and reported corn yields *at the state* level was good. For example, model simulated state average corn yield for 12 of the Corn Belt states (all but Kentucky) are compared to detrended state-level average yields from the NASS database over the period 1974–2019 in Figure A4.

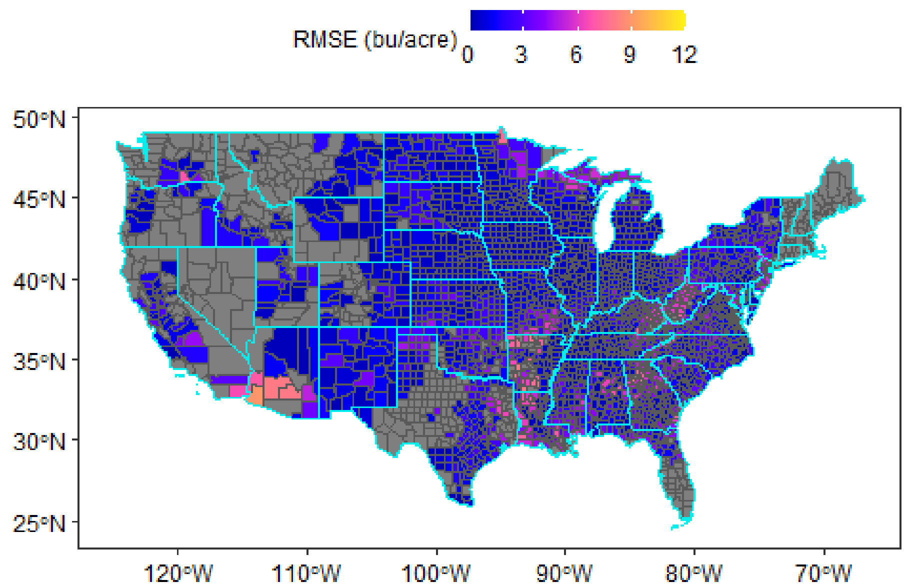

Figure A3. Mean RMSE of county average model yield simulations relative to detrended actual yield (NASS database) over the period 1974-2019. Actual yields were detrended relative to 2019, which had national average yield of about 168 bushels per acre.

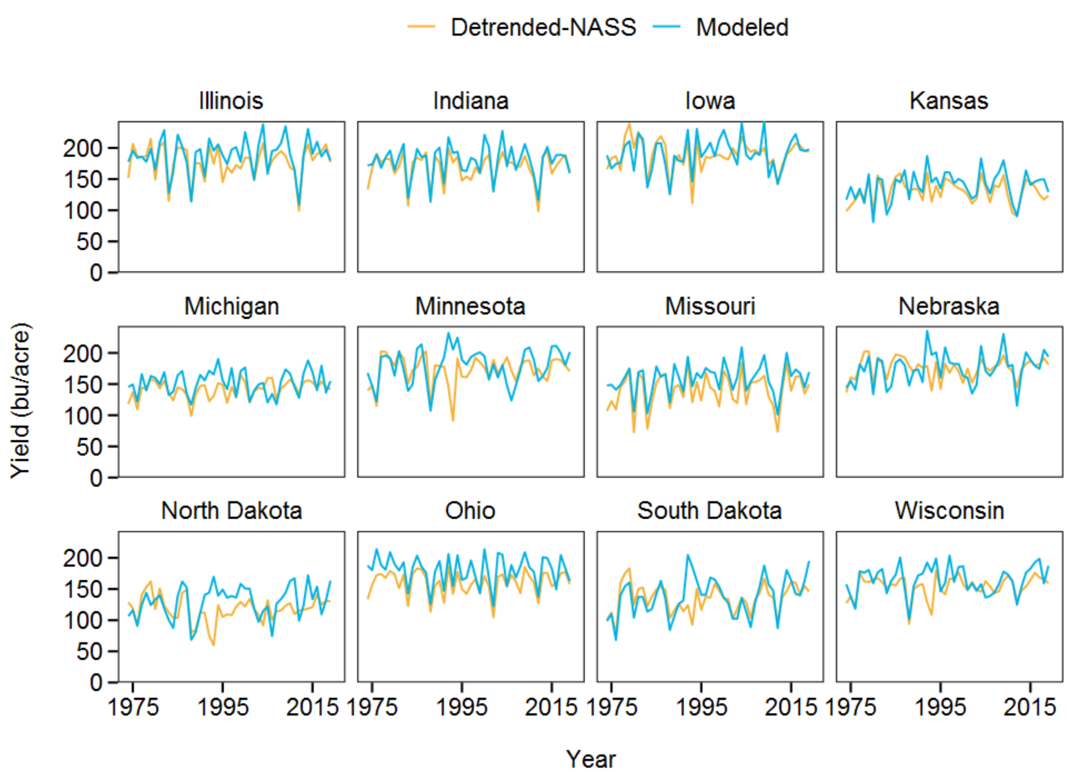

Figure A4. Time series of state average modeled and detrended actual corn yields (bushels per acre) over the period 1974-2019 for 12 Corn Belt states (all but Kentucky). Orange lines indicate NASS area-weighted yield values detrended to the year 2019. Blue lines are area-weighted output from the model parameterized for 2019 crop genetics (yield potential), management practices, and area of rainfed and irrigated corn harvested in each county.

Appendix B: Observed Weather and Simulated Climate Change

Observed Weather Trends During the 1974–2019 Period

Whole-Year (January–December) Weather Trends

Across the 13-state Corn Belt study region during the historical-weather experiment period 1974–2019, *whole-year* area-weighted (i) total precipitation increased 20.9 mm per decade, (ii) average daily T_{min} increased 0.28°C per decade, and (iii) average daily T_{max} *decreased* 0.004°C per decade. These results are based on simple linear regression analysis (ordinary least squares method) of the gridded NOAA CPC historical weather data, which will not account for any cyclical change(s) over the 46-year study period.

There was considerable variation between states, with average increases of precipitation ranging from 6.9 mm (Ohio) to 32.1 mm per decade (Wisconsin), rates of increase of average daily T_{min} ranging from 0.07 (Kansas) to 0.49°C per decade (Ohio), and rates of change of average daily T_{max} ranging from −0.18°C (South Dakota) to +0.18°C per decade (Ohio) (Table B1). It is noteworthy that five of the 13 Corn Belt states experienced a *decrease* in whole-year average T_{max} during the historical-weather experiment period, with the region experiencing a slight decrease in whole-year average daily T_{max}. Both results contrast with the national and global average air temperature increases during that period but are nonetheless consistent with previous reports of U.S. 'warming holes' in during winter/spring in the Southeast and during summer/autumn in the Midwest (e.g., Partridge et al., 2018).

Table B1. Average rates of change of area-weighted *whole-year* (12-month) total precipitation (mm per decade), average daily T_{min} (°C per decade), and average daily T_{max} (°C per decade) reported for the historical-weather experiment period 1974-2019 for each state in the 13-state study region (derived from NOAA CPC gridded daily weather data).

State	Precipitation	T_{min}	T_{max}
Illinois	21.6	0.31	0.12
Indiana	28.1	0.36	0.13
Iowa	23.6	0.13	−0.02
Kansas	27.9	0.07	0.02
Kentucky	12.9	0.42	0.10
Michigan	17.3	0.42	0.05
Minnesota	9.0	0.37	−0.07

State	Precipitation	T_{min}	T_{max}
Missouri	23.7	0.35	0.03
Nebraska	23.0	0.15	−0.01
North Dakota	17.0	0.30	−0.06
Ohio	6.9	0.49	0.18
South Dakota	25.7	0.19	−0.18
Wisconsin	32.1	0.37	0.01

Summer (June–August) Weather Trends

During the historical-weather experiment period 1974–2019, *summer* area-weighted (i) rainfall total increased 7.0 mm per decade, (ii) daily average T_{min} increased 0.21°C per decade, and (iii) daily average T_{max} *decreased* 0.16°C per decade. The Corn Belt–wide change in rainfall was a balance between increases in 10 states and decreases in the three others (Table B2). The largest state-level increases in summer rainfall were in Kansas, North Dakota, Nebraska, South Dakota, and Missouri, which are all in the western part of the Corn Belt. All Corn Belt states had increases in summer T_{min} with the largest increases in the eastern part of the study region (Michigan and Ohio).

The significant *decrease* in Corn Belt summer T_{max} was driven by decreases in 11 of the 13 states, with the increases in the other two states, Kentucky and Ohio, being only 0.01 and 0.08°C per decade, respectively Table B2). The largest declines in summer T_{max} were in the western portion of the Corn Belt, in this case South Dakota, North Dakota, Iowa, and Minnesota, which partially overlapped with the states experiencing the largest increases in summer rainfall. That portion of the Corn Belt also saw the largest decline in summer T_{max} during the period 1960–2019 in a similar analysis by Basso et al. (2021), who saw no regional trends in T_{max} from 1990 onwards.

Table B2. Average rates of change of area-weighted summer (June–August) total precipitation (mm per decade), average daily T_{min} (°C per decade), and average daily T_{max} (°C per decade) reported for the experimental period 1974-2019 for each state in the 13-state Corn Belt study region (derived from NOAA CPC gridded daily weather data).

State	Precipitation	T_{min}	T_{max}
Illinois	7.6	0.25	−0.07
Indiana	4.6	0.22	−0.05
Iowa	7.2	0.11	−0.25
Kansas	17.7	0.07	−0.14
Kentucky	2.5	0.31	0.01
Michigan	−1.2	0.35	−0.08
Minnesota	−1.3	0.24	−0.25
Missouri	10.9	0.31	−0.15

State	Precipitation	T_{min}	T_{max}
Nebraska	12.0	0.06	−0.20
North Dakota	8.2	0.19	−0.22
Ohio	−7.2	0.41	0.08
South Dakota	10.2	0.08	−0.38
Wisconsin	7.8	0.30	−0.09

The increase in T_{min} coupled with smaller increases, or in most cases decreases, in T_{max}, caused a decline in annual average daily temperature range (calculated as $T_{max} - T_{min}$ for each day) over the 1974–2019 historical period across the Corn Belt.

Across the Corn Belt states there was considerable county-level variation in trends in summer rainfall, T_{min}, and T_{max} over the period 1974–2019 (Figure B1). Increases in rainfall were most prominent in the southwestern portion of the study area. Increases in T_{min} were most prominent in the eastern portion of the study area, and T_{max} declines were most prominent in the west-central portion of the study area.

GCM-Derived Weather: Comparison to Observations During the 1974–2019 Period

GCM output can be compared to historical *climate* data, and in fact this is an important part of a typical GCM evaluation process. We carried out such a comparison, across the Corn Belt, between the downscaled GCM output and the NOAA CPC gridded weather data.

Although direct comparisons of downscaled GCM output with historical *weather* data is possible, there is no expectation that GCM results for a date (or year) will correspond to that historical date (or year). GCMs are not designed, nor anticipated, to have precise correspondence to individual days or years, but rather to reflect the longer-term climate scale and changes along that climate scale. For this reason, we used a 10-year moving average of summer (June-August) total rainfall and summer average T_{min} and T_{max} of both the NOAA CPC historical weather data and the downscaled output from each GCM for the historical study period 1974–2019 to compare the two in a more climate-centered view. We assumed that the NOAA CPC accurately reflected the historical Corn Belt climate over that 1974–2019 period, and refer to it as ‘observed’ weather or climate. We found significant differences between that observed climate history and the simulations/projections of each GCM forced by observed atmospheric greenhouse gas concentrations for the period 1974–2005 and RCP 8.5 atmospheric greenhouse gas concentration trajectories for the period 2006–2019 (Figures B2–B4).

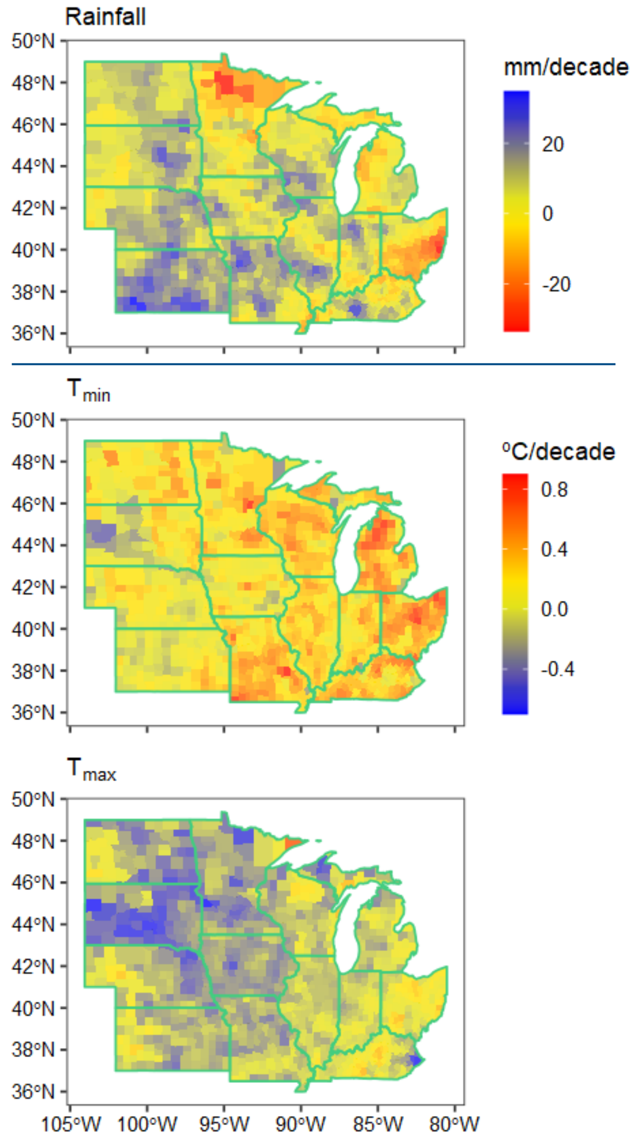

Figure B1. Average rates of change of summer (June–August) rainfall (top panel; mm per decade), T_{min} (middle panel, °C per decade), and T_{max} (bottom panel, °C per decade) in each Corn Belt–state county. Gridded daily minimum and maximum air temperatures.(0.50 × 0.50° latitude/longitude) and daily total precipitation (0.25 × 0.25° latitude/longitude) data from NOAA CPC were mapped onto each county. Rates of change were obtained by linear regression of county average values for each summer on year number during the 1974–2019 period.

Summer Rainfall

In most states there was a slight increase in observed summer rainfall over the 1974-2019 period. This generally was reflected in downscaled GCM results, although for some states (e.g., Illinois, Indiana, and Iowa) the GCMs, except GFDL-CM3, indicated a modest reduction in rainfall toward the end of that period (Figure B2).

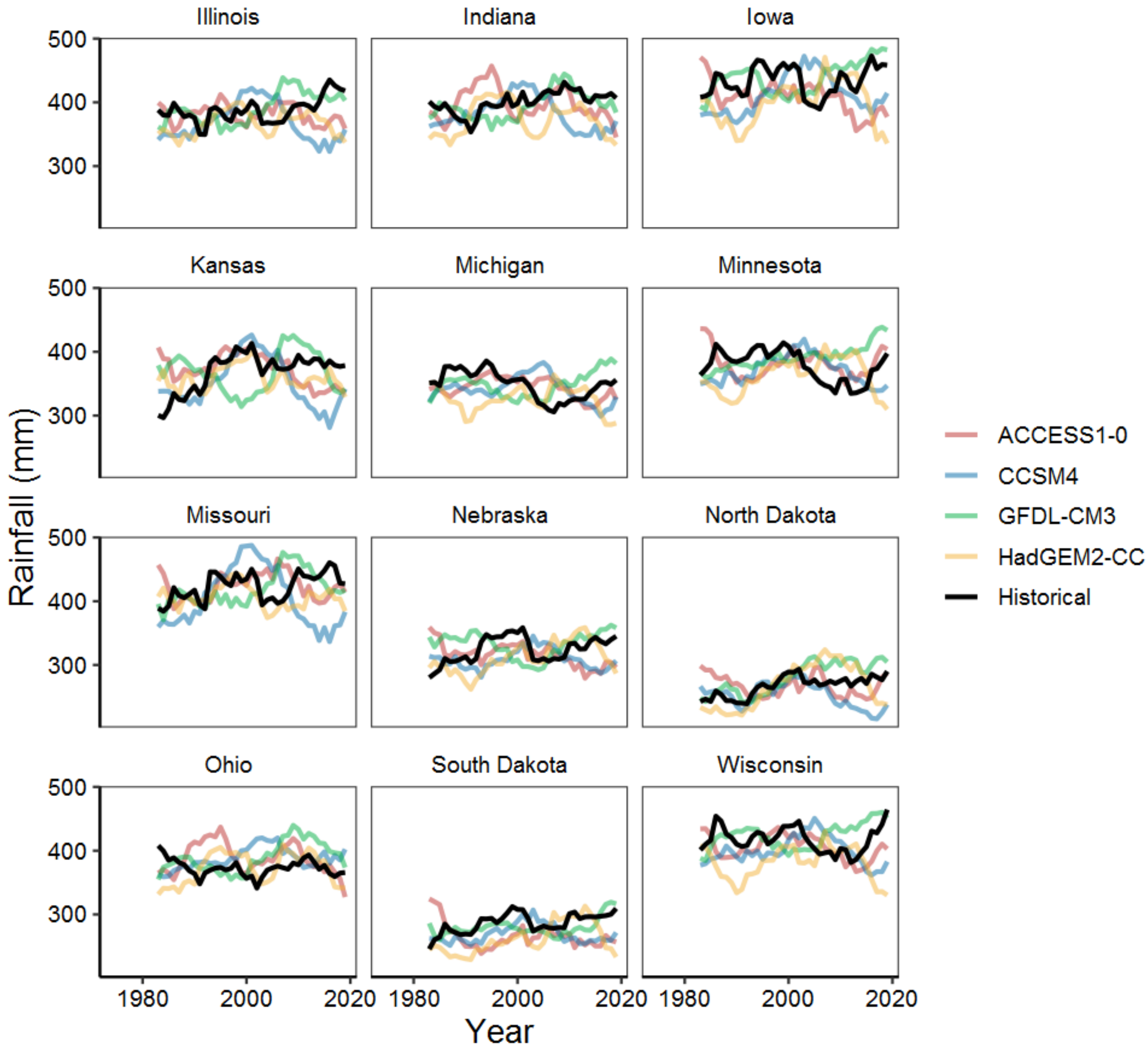

Figure B2. Ten-year simple moving average summer (June-August) total rainfall during the 1974-2019 period (first averaging period was 1974-1983 and plotted at 1983) in the historical NOAA CPC database (black line) compared to simulations of downscaled output from the four GCMs with historical (1974-2005) and RCP 8.5 (2006-2019) atmospheric greehouse gas concentration forcings (colored lines). Results for Kentucky not shown.

Summer T_{min}

There was a small increase in observed summer average daily T_{min} in many states during the period 1974-2019. This generally was reflected in downscaled GCM results, although for some states (e.g., Iowa, Kansas, Minnesota, Nebraska, North Dakota, and South Dakota) GCM results indicated a greater increase in summer T_{min} than observed toward the end of that period (Figure B3). This was especially the case for the CCSM4 GCM in the important corn-producing states Iowa, Minnesota, and Nebraska, as well as North Dakota and South Dakota. Increase in T_{min} (specifically, nighttime temperature) has been cited as a cause of yield limitation in corn (Angel et al., 2018) and rice (Peng et al., 2004), with increased nighttime crop respiration mentioned as contributing factors in both cases. It may, therefore, be important to more fully understand causes, magnitudes, and consequences of differences between observed (historical) weather data and downscaled GCM simulations of summer T_{min}.

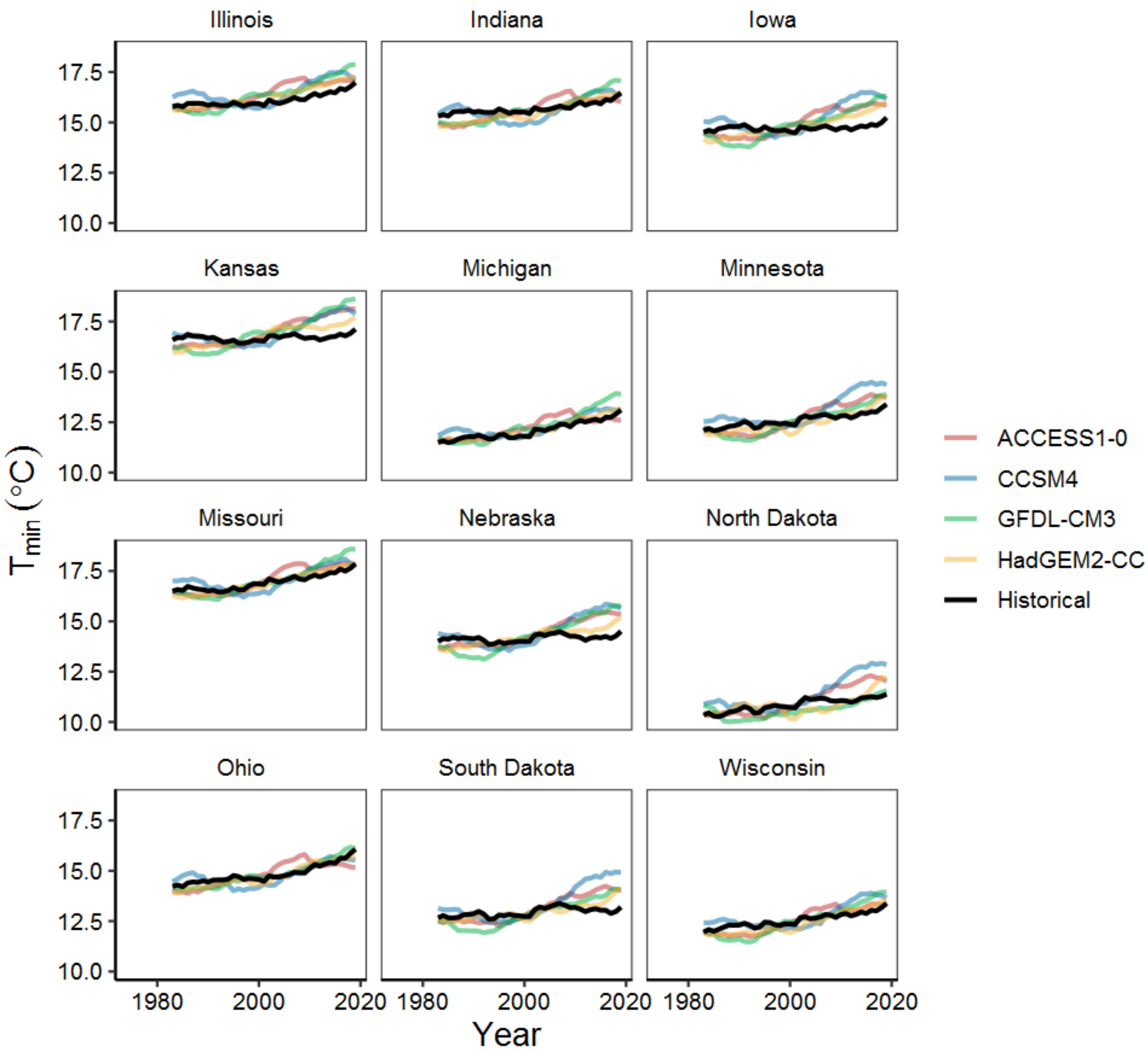

Figure B3. Ten-year simple moving average summer (June-August) T_{min} during the 1974-2019 period (first averaging period was 1974-1983 and plotted at 1983) in the historical NOAA CPC database (black line) compared to simulations of downscaled output from the four GCMs with historical (1974-2005) and RCP 8.5 (2006-2019) forcings (colored lines). Results for Kentucky not shown.

Summer T_{max}

Observed summer average daily T_{max} was generally stable and even *declining* in some states during the full 1974–2019 period, which is a hallmark of the summer U.S. Midwestern warming hole. This was in contrast to the downscaled results from each GCM that showed summer T_{max} increases, in most states, on the order of 2°C greater than observed toward the end of the 1974–2019 period (Figure B4). Similar behavior was also exhibited by other CMIP5 GCMs not used in this study.

Large differences between observed and GCM-projected T_{max} during any portion of the historical or future climate periods might cause significant discrepancies between modeled and actual crop water stress, through greater evaporation rates in the GCM-derived climates relative to the observed climate. It might also result in more frequent and more severe high-temperature stresses with the GCM-derived climate relative to the observed climate. Warmer GCM-derived climates would also reduce the period of crop growth relative to the observed climate, through accelerated crop developmental rate and a shortening of the grain filling period. Any shortening of the grain filling period would in turn be expected to reduce yield (Pritchard & Amthor, 2005).

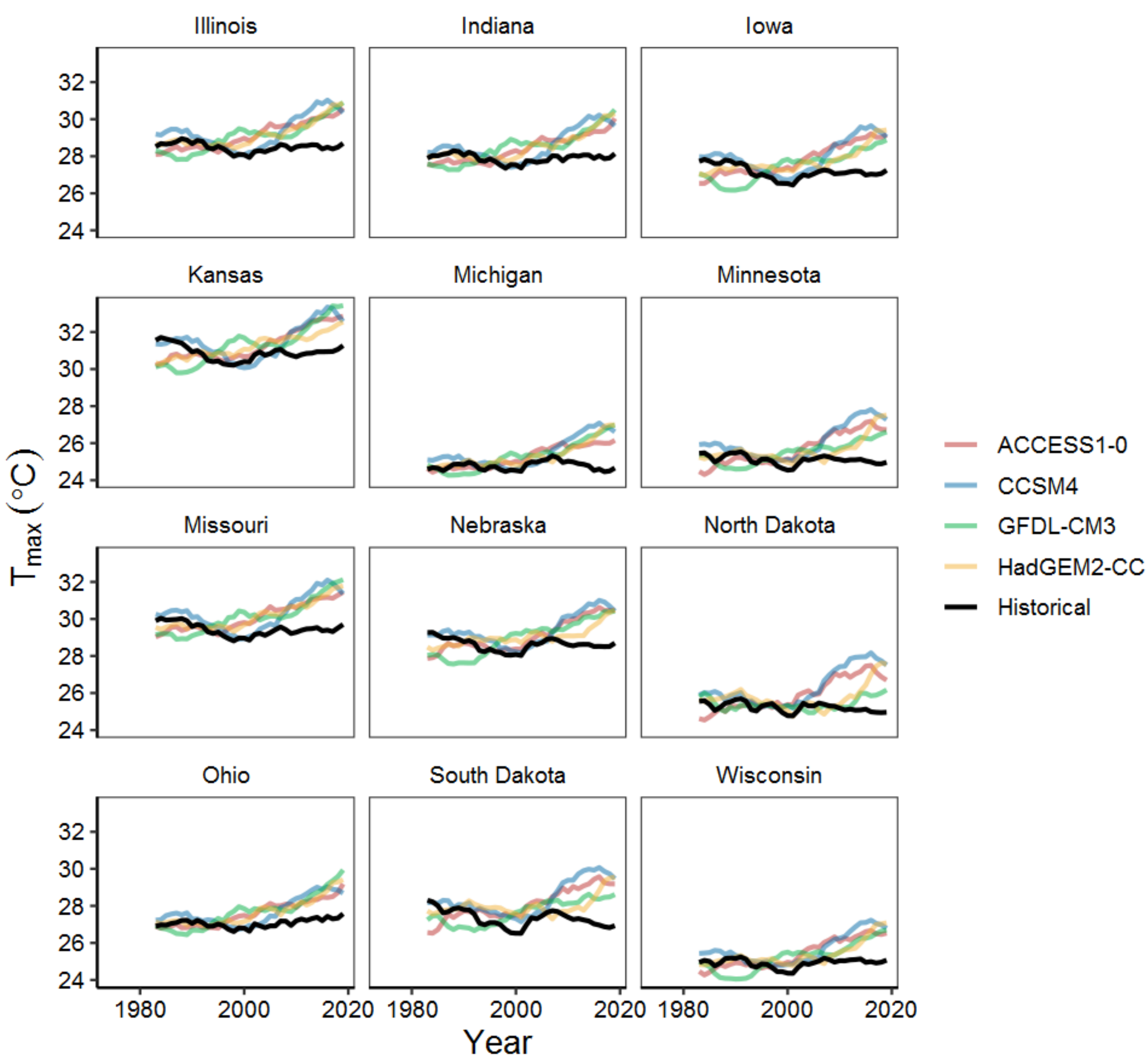

Figure B4. Ten-year simple moving average summer (June-August) T_{max} during the 1974-2019 period (first averaging period was 1974-1983 and plotted at 1983) in the historical NOAA CPC database (black line) compared to simulations of downscaled output from the four GCMs with

historical (1974-2005) and RCP 8.5 (2006-2019) atmospheric greenhouse gas concentrations (colored lines). Results for Kentucky not shown.

Diel Temperature Range

Historical observations of greater increases in summer T_{min} than in summer T_{max}, or of increases in summer T_{min} in combination with decreases in summer T_{max}, resulted in contractions in observed summer diel temperature range in all Corn Belt states during 1974–2019. To the contrary, none of the four GCMs simulated a contraction in diel temperature range, either over the 1974–2019 historical period or the climate-change-scenario experimental period (see below). An underestimation (or lack) of negative trends in diel temperature range simulated by GCMs, including CMIP5 GCMs, has previously been noted (Braganza et al., 2004; Lewis & Karoly, 2013).

GCM-derived Climate Simulations for the 1991–2055 Period

Across the 13-state Corn Belt study region during the climate-change-scenario experimental period 1991–2055, *whole-year* (January-December) area-weighted precipitation increased in all states for the GFDL-CM3 projections, decreased in all states for the ACCESS1-0 and CCSM4 projections, and decreased in six states (increasing in the other seven states) for the HadGEM2-CC projections.

Summer (June-August) rainfall declined over the 1991-2055 experimental period in all states for the downscaled ACCESS1-0 and HadGEM2-CC projections, with greatest reductions for ACCESS1-0 in all states but North Dakota (Figure 6). Summer rainfall declined in all states except Indiana for the CCSM4 projections and increased in all states for the GFDL-CM3 projections. Increased summer rainfall from the GFDL-CM3 GCM has the potential to reduce frequency of modeled drought, and possibly increase the frequency of modeled floods and/or water logging stress. Summer rainfall reductions for the other models, especially the ACCESS1-0 model, would be expected to increase the frequency and extent of modeled crop water stress and resulting yield loss.

Both summer daily average T_{min} and T_{max} increased in all states for all four GCMs (Figure 6). The GFDL-CM3 and HadGEM2-CC GCMs simulated the greatest increases in T_{min} across most states whereas T_{max} increases were largest for ACCESS1-0 in all states but Missouri and North Dakota.

The generally larger increases in summer T_{max} for the ACCESS1-0 GCM compared to the other three GCMs implied a greater number of summer days with potentially stressful high temperatures in the crop growth simulations. These could include heat waves that can reduce seed set by damaging pollen and eggs before flowering, disrupting fertilization of eggs during flowering, and causing mortality of embryos after flowering. This can in turn reduce the number of seeds eventually harvested from each corn plant.

A reduced number of seeds per plant is often related to reduced yield in corn, and in other grain crops, because average seed size (mass) is generally more stable than number of seeds per plant (Sadras, 2007). The general result is that a reduction in seed number is not (fully) compensated for by increased size of surviving seeds.

Diel Temperature Range

A comparison of rates of change in summer T_{min} and summer T_{max} across GCMs and states in Figure 6 indicates greater increases in T_{max} than T_{min} over the experimental period. The result of that relationship was an *increase* in diel temperature range in the GCM-derived climate-change scenarios for most GCMs in most states. This is counter to recent history in the Corn Belt, which has experienced a contraction in summer diel temperature range (see above). Diel temperature range has also decreased over other regions, and globally, in the recent past (e.g., Lewis & Karoly, 2013).

Appendix C: Modeled Crop Responses to Historical Weather Stresses, 1974-2019

Crop Weather Stresses

The AIR Crop Growth and Yield Model was designed to quantitatively simulate crop responses to the major stresses directly related to soil moisture (too much or too little) and air temperature (too low or too high). The version of the model used here did not include hail or wind damage, and although these can be, and often are, of great significance at the local scale, the historically large Corn Belt–wide negative effects of weather on yield and production have *mostly* been related to variation in rainfall and temperature, either singly or in combination. Thus, the combination of (i) weather variables accounted for in the GCM climate scenarios and (ii) crop model response functions to weather can account for the quantitatively most important effects of climate variability and change on crop yield and production.

Drought

As described earlier, drought was associated with most of the large historical shortfalls in U.S. corn yield and production since the 1930s. Consistent with that history, modeled corn yield in the highest producing states was lowest in strong drought years during the 1974-2019 historical-weather experiment. This was especially true for rainfed crops, but irrigated-crop yield was also depressed by drought in some cases (Figure 10). Although years such as, e.g., 1988 and 2012, are properly characterized as ‘drought years,’ the magnitude of those droughts varied temporally and spatially across the Corn Belt. As such, we expect that modeled yield response to drought will differ between states for any particular ‘drought year,’ even being absent in some counties or states in some drought years.

Drought is sometimes associated with extreme high temperature. Because the AIR crop model simultaneously simulates effects of soil moisture content, atmospheric VPD, and temperature on evaporation from the soil, crop transpiration, biomass accumulation, and seed set, the interactive effects of water stress and high-temperature stress can be properly simulated. Therefore, modeled low yield during drought is often a combination of effects of drought (lack of rain *per se*) and coincident high-temperature stress, which is also the case in actual crops. For example, the model indicates that weather during would have caused the lowest rainfed corn yield in many of the Corn Belt states during the 1974-2019 period (with crop genetics and management practices held constant over that period). The summer drought of 1988 was one of the most extreme in U.S. history since the 1930s Dust Bowl and involved a combination of high-temperature extremes (many high-temperature records were set) and low rainfall.

Waterlogging

Waterlogging results when large water inputs from rainfall and/or river flooding exceed evapotranspiration or runoff from planted, or to-be-planted, fields. This can result in a reduction of area planted to corn and other crops, and limit yield of crops that are planted. The AIR crop model simulates any waterlogging throughout the year, and any associated crop damage during the growing season, through a daily crop and soil water balance analysis. This occurs 365 days a year for the soil component and for each day between the simulated crop emergence (following germination) and time of crop physiological maturity, at which time transpiration is halted in the model.

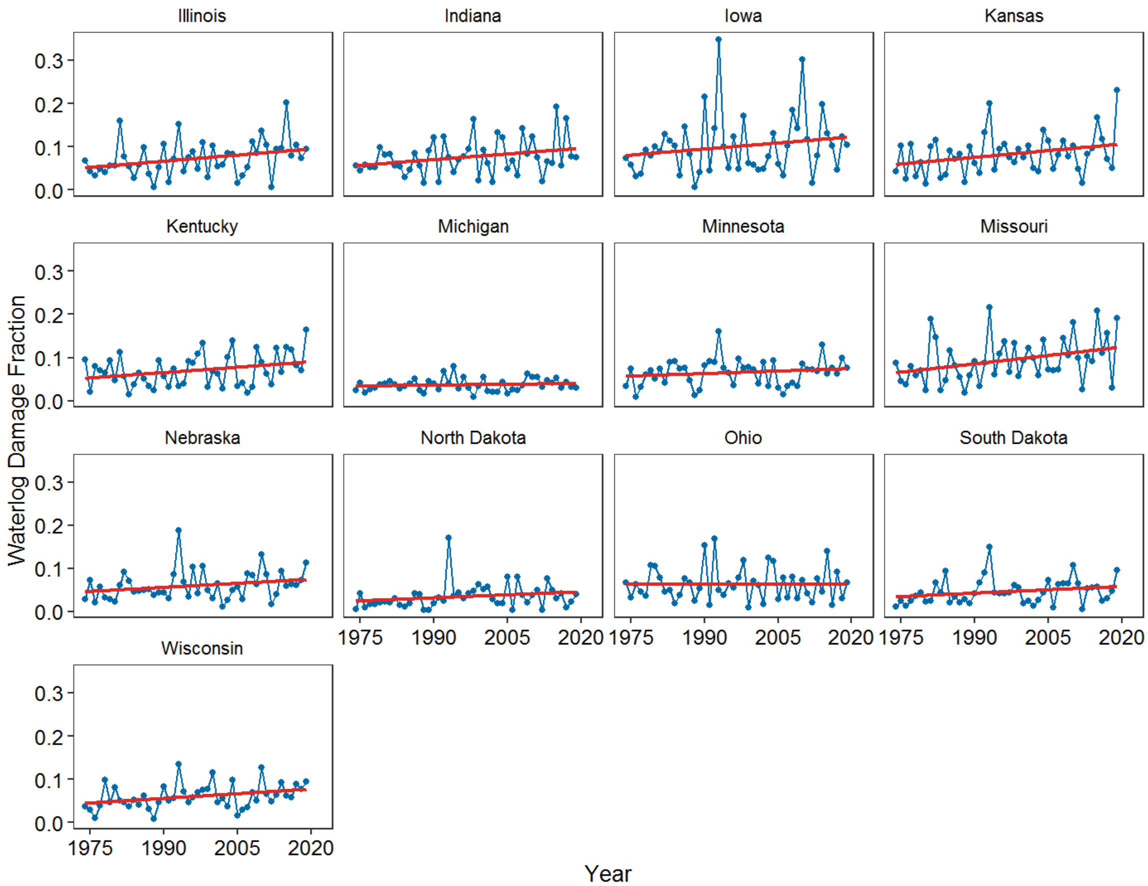

Figure C1. Simulated areal fraction of rainfed corn crop in each state suffering waterlogging damage, ranging from modest to extreme, during the historical-weather experimental period. Red lines are linear regressions of waterlogged area fraction on simulation year indicating modest increases in the areal fraction of corn crops subject to waterlogging stress.

Because of increasing whole-year and summer precipitation during the 1974-2019 historical-weather experiment period, in combination with relatively constant potential and actual evapotranspiration rates realized because of limited change in T_{max}, the extent of waterlogging in the crop model increased marginally over time. The fraction of crop in some states damaged by waterlogging increased from about 5% in the 1980s to about 10% in the 2010s; no state saw a decline in modeled waterlogging damage over the study period. Actual corn yield and production were low in 1993 (see Figure 1 for national average yield and Figure 3 for national area harvested), a result that is generally attributed in part to flooding. The model indicated significant waterlogging damage during 1993 in most of the central and western Corn Belt states (Figure C1).

Frost/Freeze Damage

Modeled freeze damage to reproductive success and grain development occurred only in the northern and western states in the historical-weather experiment (results not shown). From 1974 to 2004, modeled freeze damage was common in Michigan and

Minnesota though it was of small magnitude. Slight damage was simulated in one, two, or three years during the 1974-2019 period in Nebraska, North Dakota, South Dakota, and Wisconsin, with 2004 being a year with damage in three of those states. After 2004, increases in spring and summer T_{min} fully alleviated the modeled frost/freeze stress in the Corn Belt.

High-Temperature Stress Around the Time of Flowering

High-temperature damage to reproductive structures around the time of anthesis (i.e., flowering) can have significant negative consequences for final crop yield in corn and other grain crops in part through reduced seed set (Pritchard & Amthor, 2005). The historical-weather experiment indicated only modest (or no) occurrence of such damage during most years in most states, though the western Corn Belt states of Kansas, Nebraska, and South Dakota suffered heat-temperature damage to reproductive processes in many years, and this occurred with a slightly declining trend over time (Figure C2), consistent with the declining trend in summer T_{max} during the period 1974-2019 (Table B2; Figure B4). The generally higher summer T_{max} values in Kansas, relative to other Corn Belt states (Figure B4), provides greater opportunities for reproductive-structure damage in corn grown there.

Although high-temperature damage was generally low for most of the modeled crops, the years 1988 and 2012 saw relatively significant modeled high-temperature damage (including reduced seed set) in many of the Corn Belt states. Those years were also associated with drought, as discussed above. Hence, modeled yield reduction in those years was a combination of water stress and high-temperature stress, with the likelihood of some interactions between high temperature, evaporative demand in the atmosphere, and crop water stress.

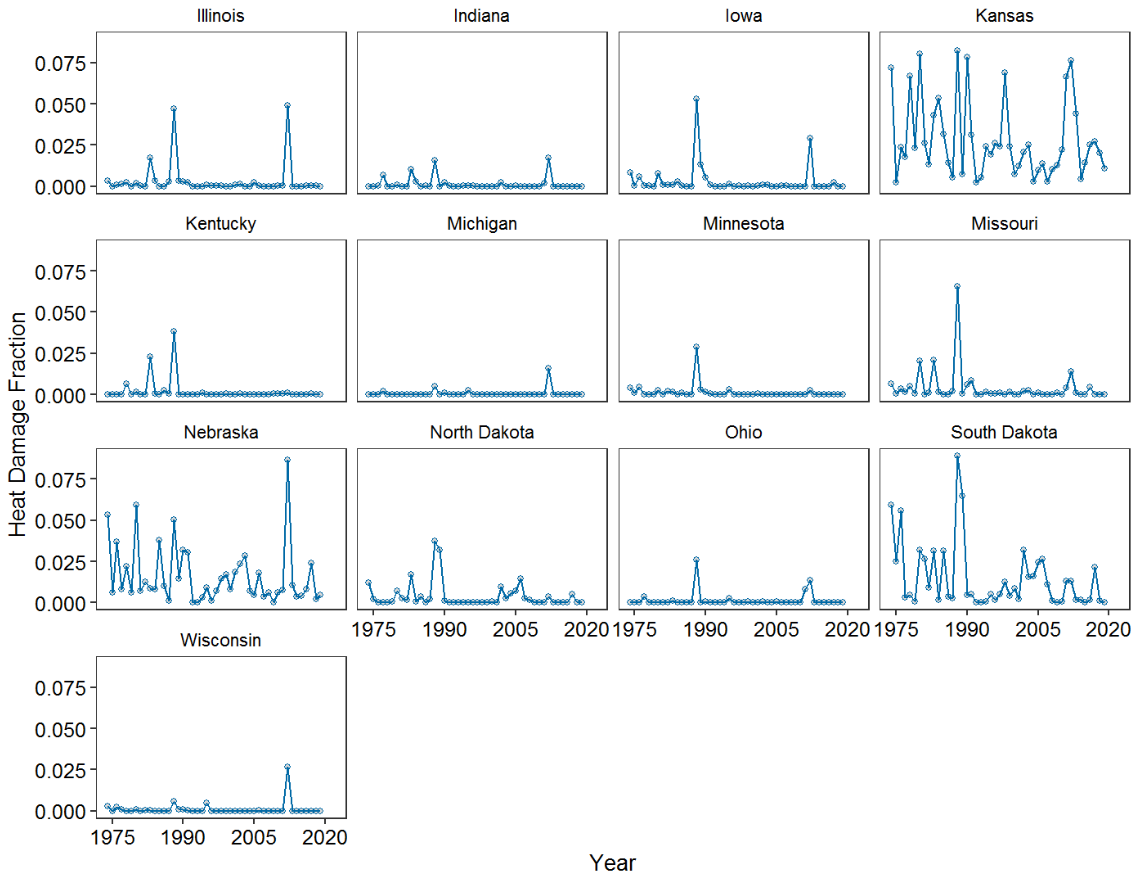

Figure C2. High-temperature damage to rainfed corn crops around the time of anthesis (flowering) as reflected by the fraction of potential seeds lost (i.e., eggs unfertilized or embryos killed) due to excessively high temperature. A value of 0.05 indicates that 5% of the seeds that would have developed were lost to high-temperature stress.

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