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How Climate Change Will Impact U.S. Corn, Soybean and Wheat Yields:

A county-level analysis of climate burdens and adaptation needs in the Midwest

Environmental Defense Fund

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About this report

Environmental Defense Fund and Two Degrees Adapt worked together to explore how climate change will impact crop yields by 2030 and 2050. We selected corn in Iowa, soybeans in Minnesota and winter wheat in Kansas to represent climate impacts on the commodity crops most important to food supply chains in the U.S. and around the world. The process used, and trends observed, can be extended to other crop and geography combinations.

We used an ensemble of 20 different climate models to explore a range of possible climate changes. This publicly available climate model data was downscaled to 16 square kilometers (4000 acres) using peer-reviewed methods. We then coupled the localized climate data with crop yield models to predict the impacts of climate change on crop yields. We averaged this localized, gridded yield impact data at county scales to make the information more relevant and actionable for policymakers, farmers and other agricultural decision-makers.

Qualitative interviews with farmers and agricultural experts in Iowa, Minnesota and Kansas provided additional insights about how climate change is likely to affect crop production and about adaptation methods already underway in the three states.

Executive summary

U.S. farmers are used to managing variable weather, and they have harnessed technological advances to steadily increase yields of corn, wheat and soybeans for the last 70 years. Climate change threatens to slow or reverse this productivity as soon as 2030, with potentially profound consequences for agricultural economies and global food supplies.

Weather is not only more extreme but also more variable than ever before. In many of the most productive agricultural counties in the U.S., higher temperatures and changes in rainfall will lower yields of staple crops below what technological innovation and improvements in management practices can recoup. We describe the impact of climate on yields as a climate boost (if yields are increased compared to what they would be without climate change) or a climate burden (if yields are decreased compared to what they would be without climate change). By 2030:

- 100% of Iowa counties will see climate burdens of more than 5%, and more than half will see climate burdens of more than 10%.
- 56% of Minnesota counties will see climate burdens of more than 5%, and 17% of counties will see climate burdens of more than 10%.
- 9% of Kansas counties will see climate burdens on wheat of more than 5%. While no counties will see climate burdens of more than 10% by 2030, one comes close at a 9.3% burden.

Climate burdens will increase through 2050 with more counties experiencing climate burdens, and the size of these climate burdens increasing. This production shortfall will undermine global efforts to grow 50% more food by mid-century to feed a growing population.

The magnitude of these impacts in such a short timeframe suggests that we are running out of time to make the necessary climate adaptations to maintain agricultural productivity and food supplies.

Adaptation efforts, whether incremental or transformative, take time to work. The sooner we act, the better for farmers, food security and rural economies.

Climate impacts and adaptation strategies are highly local

Row crop farmers across the Midwest will face an increasing climate burden on crop yields, but the extent of this burden will vary geographically and by crop.

Within individual states, some counties may see a climate boost while others see a climate burden, and the intensity of the climate burden can vary tremendously. For example:

- Farmers in Iowa's southern counties will experience greater climate burdens than those in other counties. Driven by increases in extreme heat, the predicted climate burden on yields in Davis County is 25% in 2030 and 44% in 2050.
- Farmers in some counties in Kansas may experience climate boosts, but in other counties may face climate burdens. The severity will depend on complex interactions of soils, irrigation and climate change. From 2030 to 2050, eight counties in the central part of the state shift from experiencing relatively little climate impact to experiencing a climate burden of 5% or higher.

- Minnesota soybean farmers will experience a mix of boosts and burdens. Some areas will see a climate-induced boost to yields from more moderate temperatures. In the northern part of the state, extreme heat will create a significant climate burden.

Successful adaptation efforts must be as localized as possible. For the first time, this report provides farmers and policymakers with the hyperlocal information they need to target interventions and investments. It models climate impacts in 2030 and 2050 down to 4,000 acres or 16 square kilometers — smaller than county boundaries.

Adaptation efforts, whether incremental or transformative, are urgent

This report uses models with optimistic climate assumptions — that emissions will peak by mid-century and then decrease, and technological innovation (together with improvement in management practices) will continue at historic rates. Climate impacts on agriculture by 2030 and 2050 could be much worse than the scenarios we present in this report if global emissions continue to rise past mid-century and/or yield increases from innovation and improved management do not keep pace with past growth. Adaptation is necessary and urgent.

Our research uncovered some promising adaptation options that are already being implemented in Iowa, Minnesota and Kansas. Some adaptation options, such as adopting farming practices that improve soil heath, are "no-regrets" options that are likely to benefit production regardless of climate change and are already underway on many farms. Other adaptation approaches cover a spectrum from incremental to transformative. Having a range of options is important because it allows for the least disruptive approach — such as using an improved variety of the current crop — to be deployed first, and then more transformative options — such as growing a new crop altogether — to be deployed later, as needed. However, the lead time for transformative adaptation is much longer than for incremental adaptation, so planning for transformation must begin long before it is needed, even while incremental approaches are still being deployed. Many counties in our study area need to begin that planning in the next couple of years.

Whether incremental or transformational, the scale of change needed is likely to be immense. Some experts have suggested that meeting the challenges of climate change will require adapting current cropping systems through technological innovations on the scale of the Green Revolution and the introduction of transgenic seeds.[1,2,3] Other experts suggest that — given the levels of adaptation potentially needed and the level of investment required to adapt current cropping systems — it makes more sense to shift to alternative cropping systems, which could also deliver greater environmental and nutritional benefits.[4,5] Regardless, it's clear that investment in adaptation needs to begin now for the adaptation measures that will be needed in less than a decade.

Traditional farm safety net programs such as crop insurance will be necessary but insufficient to meet the scale of the climate challenge. The U.S. Department of Agriculture's Economic Research Service estimates that without adoption of climate adaptation measures, the cost of the Federal Crop Insurance Program could increase by over a third in the second half of this century.[6] There are opportunities to support farmers in climate adaptation to minimize their losses and protect their futures, both within the crop insurance program and through additional public and private investment in adaptation solutions and technical support.

We hope that this report will stimulate conversations across the agricultural community about the importance of preparing for climate change. County-level estimates of climate impacts provide a valuable tool for farmers who wish to understand how their region will be affected by increasing temperatures and variable rainfall. Policymakers may wish to understand the scale and geographic variability of likely damages to crop production and provide support to help farmers and rural communities minimize these damages. Specifically, we recommend that public and

[1] Pingali, Prabhu L. "Green revolution: impacts, limits, and the path ahead." Proceedings of the National Academy of Sciences 109.31 (2012): 12302-12308.

[2] Llewellyn, Danny. "Does global agriculture need another green revolution." Engineering 4.4 (2018): 449-451.

[3] Ortiz-Bobea, Ariel, and Jesse Tack. "Is another genetic revolution needed to offset climate change impacts for US maize yields?." Environmental Research Letters 13.12 (2018): 124009.

[4] De Schutter, Olivier, and Gaëtan Vanloqueren. "The new green revolution: how twenty-first-century science can feed the world." Solutions 2.4 (2011): 33-44.

[5] Altieri, Miguel A., et al. "Agroecology and the design of climate change-resilient farming systems." Agronomy for sustainable development 35.3 (2015): 869-890.

[6] Crane-Droesch, Andrew et al. Climate change and agricultural risk management into the 21st century. U.S. Department of Agriculture Economic Research Service. July 2019. https://www.ers.usda.gov/webdocs/publications/93547/266.pdf?v=9932.1. Accessed 24 August 2022.

private investments in agricultural climate solutions:

1. Take an integrated approach that considers the importance of both climate mitigation and adaptation.
2. Increase research and development funding to expand the suite of adaptation options, from incremental to transformational.
3. Prioritize support for farmers adapting to climate change, including making adjustments to traditional farm safety net programs and expanded technical assistance.

The scale of the climate burden on crop yields is daunting, but adaptive solutions exist. If we move quickly and deliberately during this decisive decade, we can protect crop yields, farmer livelihoods and global food supplies.

BOX 1:

Definitions

Climate adaptation: Climate adaptation refers to efforts to prepare for climate impacts that are unavoidable because of past climate pollution that is already in the atmosphere. Adaptation efforts for agriculture can include improving soil health to help crops better withstand variable rainfall or growing different crop varieties that are better suited to our new climate reality.

Climate boost: Climate boost is an increase in yields resulting from climate change. If the yields predicted for a future date with climate change are larger than the yields predicted for that date without climate change, the difference between these yields is the climate boost. It occurs when the positive impacts of climate change exceed the negative impacts of climate change, for example when warming leads to more growing-degree days. In general, this boost is more likely to accrue at higher, colder latitudes.

Climate burden: Climate burden is a decrease in crop yield resulting from climate change. If the yields predicted for a future date with climate change are smaller than the yields predicted for that date without climate change, the difference between these yields is the climate burden. It occurs when the negative impacts of climate change exceed the positive impacts of climate change. For example, a burden on crop yields can happen when extreme heat decreases crop yields by more than warmer temperatures or technological advancement can boost crop yields.

Climate mitigation: Climate mitigation refers to efforts to actively cut emissions of GHGs that accelerate climate change or efforts that maintain or enhance GHG removals by carbon sinks. Carbon dioxide is the biggest determinant of the amount of climate change we'll experience this century. Agriculture has a key role to play in mitigating two other GHGs that have shorter lifespans than CO_2 but a bigger impact on the rate of near-term warming — nitrous oxide from excess fertilizer and methane from livestock.

Growing-degree days: Growing-degree days are heat units used as a metric to estimate the growth of crops during the growing season. These are calculated based on the high and low temperatures during a day. They measure the accumulated average daily temperatures that are above a minimum temperature for plant growth to occur. Corn and soybeans need a minimum temperature of 50°F (10.0°C) for growth, and winter wheat needs a minimum of 40°F (4.4°C). They are not reported as traditional 24-hour days. As an example, corn requires 1,600 to more than 2,500 accumulated growing-degree days.

Killing-degree days: Killing-degree days are a similar metric as growing-degree days, but they instead measure the accumulated temperatures in excess of a maximum growth threshold. These temperatures are, at best, too hot for crops to grow and, at worst, damage or kill the crop. For corn, soybeans and winter wheat, maximum temperatures are those above 84°F (28.9°C), 85°F (29.4°C) and 82°F (27.8°C), respectively.

Representative concentration pathways, or RCPs: RCPs are a shorthand way to reference different scenarios for how severe climate change will be by the year 2100. They are based on assumptions about how factors like population growth, technology development and land use will influence future levels of new GHG emissions, cumulative concentrations from past emissions and levels of expected warming. For example, RCP4.5, which is what we use in this report, assumes new climate pollution will peak before 2050 and slowly decline thereafter, resulting in a climate that is, on average, 4.3°F (2.4°C) warmer by mid-century.

Introduction

The first two decades of the 21st century have seen increasing and unprecedented global ambition to address climate change. Despite this progress, a lack of coordinated efforts between countries, and competing priorities, such as economic development and geopolitics, means that the world is still on track for a global average temperature rise of 3.6 to 5.4°F (2 to 3°C) by 2100 — even if all countries meet their 2015 Paris Agreement climate pledges.[7]

The U.S. is projected to warm more than the global average. By 2050, climate projections for the lower 48 states show temperatures 1 to 5°F (0.5 to 2.8°C) greater than temperatures in the recent past (1986-2015). By 2100, the same projections show areas with 2 to 10°F (1.1 to 5.6°C) of additional warming.[8] In other words, a heat wave of today may become the norm by mid-century and seem cool by 2100.

Climate change is not only a problem for the future — its impacts are already being experienced today. The world has warmed 1.8°F (1°C) above the pre-industrial global average temperature, creating cascading and devastating impacts in stronger floods, fires and extreme heat.[9]

While farmers are accustomed to variable weather, we have entered a new era in which weather is both more extreme and more variable than we have known in the past. As an example, the Millennium Drought at the beginning of this century in Australia was the worst since European settlement and devastated 50% of the country's agricultural land.[10] The 2012 drought in the U.S. Corn Belt caused agricultural losses in excess of $30 billion.[11] In 2019, historic flooding on the Missouri, Arkansas and Mississippi rivers caused over $20 billion in damage[12] and ruined 20 million acres of cropland,[13] and in 2020, a derecho damaged crops on 3-4 million acres in Iowa.[14] These examples foreshadow the dangerous and costly impacts of future climate change.

[7] IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

[8] USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [D.R. Reidmiller, et al. (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

[9] USGCRP (2017). Climate Science Special Report: Fourth National Climate Assessment, Volume 1 [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6.

[10] Heberger, Matthew. "Australia's millennium drought: Impacts and responses." The world's water. Island Press, Washington, DC, 2012. 97-125.

[11] Rippey, Bradley R. "The US drought of 2012." Weather and climate extremes 10 (2015): 57-64.

[12] "2019 was the 2nd wettest year on record for the U.S." 21 January 2020. https://www.noaa.gov/news/2019-was-2nd-wettest-year-on-record-for-us. Accessed 24 August 2022.

[13] Ahmed, Amal. "Last year's historic floods ruined 20 million acres of farmland." Popular Science, 20 January 2020. https://www.popsci.com/story/environment/2019-record-floods-midwest/. Accessed 24 August 2022.

[14] Bellemans, Nicolas et al. "How the Iowa derecho has affected 2020 crops." 3 September 2020. https://www.mckinsey.com/industries/agriculture/our-insights/how-the-iowa-derecho-has-affected-2020-crops. Accessed 24 August 2022.

The food and agriculture industry in the United States is important not only as an economic engine for the country but also as a contributor to global food security. How this industry adapts to climate change will play a critical role in securing global food supplies. However, global-scale predictions for mid-century and beyond are of limited use in helping agriculture prepare for climate change. Decisions about what farmers choose to plant, where they choose to plant it, how they plan to use inputs such as water and fertilizer, and how policymakers can best support them must all be informed by more localized and nearer-term climate information. This report fills that gap, providing actionable climate information down to 4,000 acres or 16 square kilometers.

This study uses a novel analytical approach to show county-level climate impacts in 2030 and 2050 for three illustrative use cases: Iowa corn, Minnesota soybeans and Kansas winter wheat. We selected these crops and geographies to represent climate impacts on the commodity crops most important to food supply chains and in states with a large percentage of cropland acreage used for the selected crop.

To make modeled climate outcomes more relevant to farmers and policymakers making decisions today, we translated large-scale and long-term climate predictions into localized data. For each case study, we leveraged publicly available downscaled climate predictions from multiple climate models to better understand the variability of likely climate impacts within counties in each state. We then used this downscaled climate data in combination with the best-available crop models to predict the impacts of climatic changes on crop yields. Finally, for each crop and state combination, we explored climate adaptation options that are already in use and/or are anticipated to become more widespread in the next decade.

While climate-proofing U.S. agriculture is a mammoth undertaking with unique challenges for each crop and state, adaptation is possible. We hope that the issues illustrated through these three data-driven case studies will begin a much-needed national conversation about this subject. As farmers make annual decisions about which crops to plant, they may also want to plan how they will respond to coming changes, because the benefits of adaptation options may take years to accrue. Policymakers may wish to understand the scale and spatial variability of likely damages to crop production and provide support to help farmers and rural communities minimize these damages. As the most recent IPCC report on adaptation states, "Taking action now can secure our future."[15] Let's get started.

[15] "Climate change: a threat to human wellbeing and health of the planet." 28 February 2022. https://www.ipcc.ch/report/ar6/wg2/resources/press/press-release/. Accessed 25 August 2022.

How climate change will impact crop yields

How we modeled climate impacts

To explore climate change impacts in the future, climate scientists use scenarios and global models. Scenarios are projections of future GHG emissions based on assumptions about changes in population, energy use, land use change and other factors that affect GHG emissions. The projected changes in GHGs are then translated using complex global models into changes in future climate, represented by changes in temperature (warming) and precipitation.

In this study, we considered climate simulations following a climate scenario known as RCP4.5. It is a "middle-of-the-road" scenario in which GHG emissions peak before mid-century and then slowly decline. RCP4.5 results in a global average warming of about 4.3°F or 2.4°C. Society is not currently on track to curb emissions before mid-century so impacts could be much worse than the climate scenario we chose. We ran climate scenarios for the near-term (2030) and for the longer-term (mid-century, 2050).[16]

Different global climate models make different assumptions about how changes in GHG emissions translate into changes in temperature and precipitation. We used an ensemble of 20 different models, giving us a range of predicted climate changes. When changes in predicted climate outcomes are similar between different models, we can have greater confidence in the predictions.

We used publicly available climate model data "downscaled" to a 4-kilometer x 4-kilometer scale using peer-reviewed methods. This scale is equivalent to about 4,000 acres, allowing us to understand likely climate impacts at a scale relevant to farming communities. For each 4x4 km area in Iowa, Minnesota and Kansas, we therefore have a range of predicted changes in temperature and precipitation for 2030 and 2050. See Appendix A for a more detailed discussion of the climate data and downscaling approaches chosen for this research.

The downscaled climate futures showed an expected increase in temperature during the growing season. This leads to an increase in "growing-degree days," which might be anticipated to lead to higher crop yields (Figure 1). However, warmer temperatures also can lead to an increase in "killing-degree days" (Figure 2), during which a crop experiences temperatures high enough to cause damage to the plant and decrease crop yields.

The overall effect of climate change on crop production, then, depends in part on the balance between increases in "growing-degree days" and increases in "killing-degree days," as well as changes in precipitation, plant water needs and plant water availability. For Iowa corn, for example, we predict that annual growing-degrees days will increase by 11% by 2030, but killing-degree days will increase by 57% in the same timeframe, creating an overall negative impact on yields.

[16] In this report, we refer to the 40-year period centered on 2000 (1980-2020) as "historical," the 20-year period centered on 2030 (2021 through 2040) as "near-term" and the 20-year period centered on 2050 (2041 through 2060) as "mid-century."

FIGURE 1:

Percent change in growing-degree days for Iowa corn in 2030

The percent change in growing-degree days shown is for the 20-year period (2021-2040) compared to the 40-year historic period.

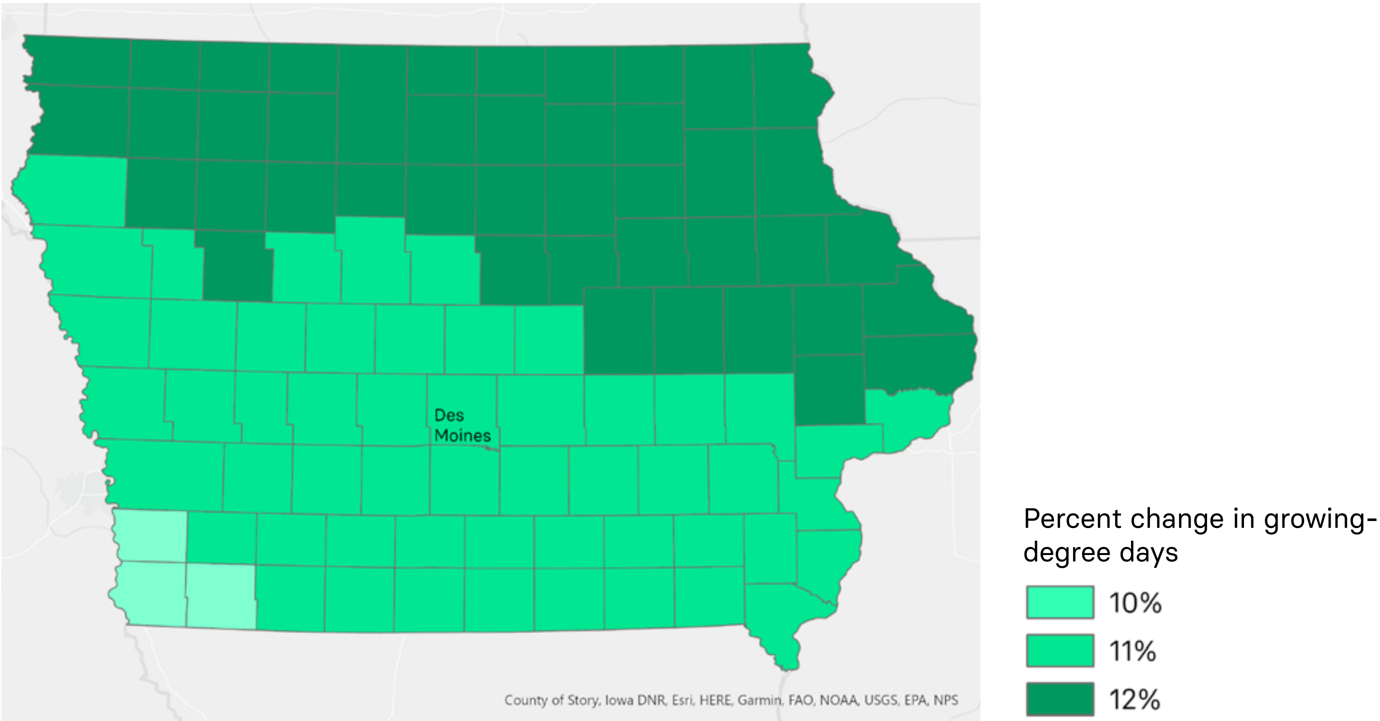
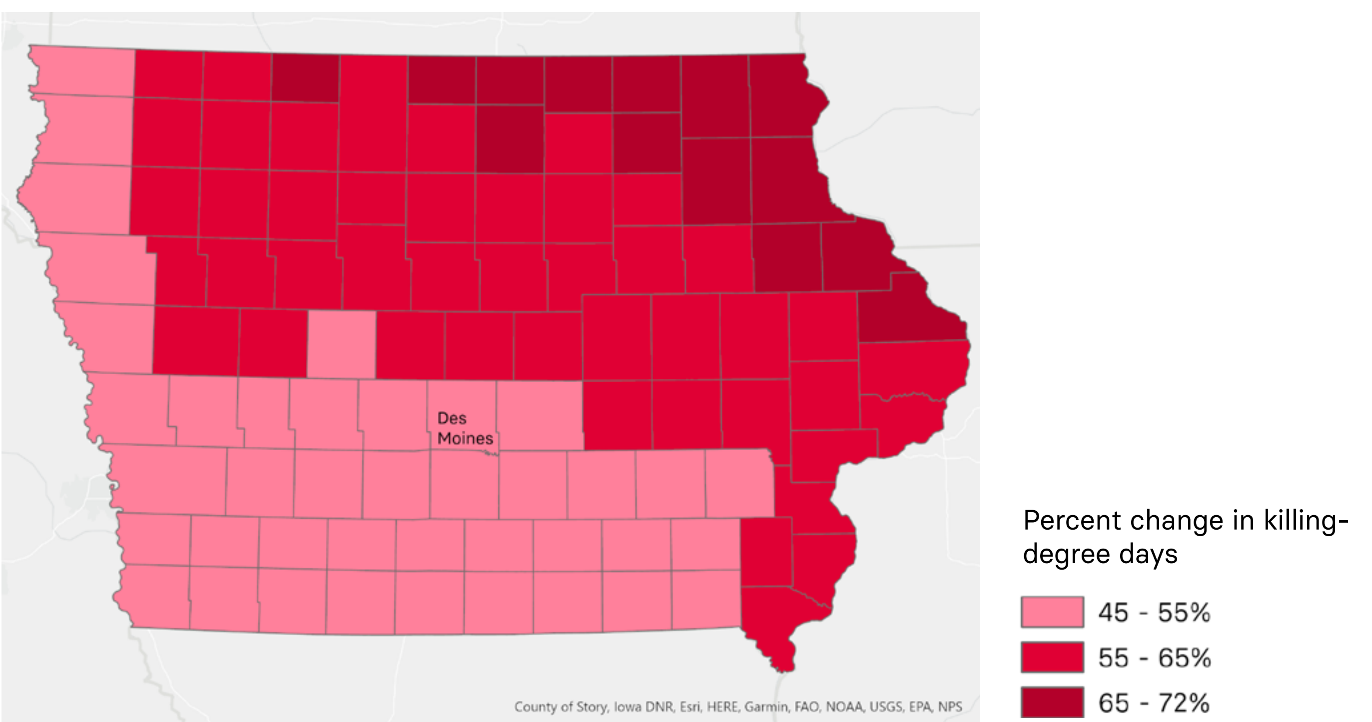


FIGURE 2:

Percent change in killing-degree days for Iowa corn in 2030

The percent change in killing-degree days shown is for the 20-year period (2021-2040) compared to the 40-year historic period.



In addition to being optimistic about future climates, we also made the optimistic assumption that crop technology innovations in the future would keep pace with past innovations and that management practices would continue to improve at historic rates. For each crop and state combination, we used statistical analysis of 40 years of historical yield data to develop a linear relationship showing how yield has increased over time. Extending this line beyond the present day and into the future shows us what future yields could be expected to be if there were no climate change and if technological developments continue to improve crop yields at historic rates.

There is no guarantee that crop yields will continue a linear increase indefinitely, however. In fact, multiple studies suggest that crop yields have already reached their highest levels and are stagnant or beginning to decline.[17, 18, 19] Declining levels of investment in agricultural R&D spending threatens the ability of technology to continue to deliver the spectacular yield growth of the past half-century.[20]

To estimate the impact of climate change on future crop yields, we used crop growth models developed by the leading scientists in each state. For each crop, these models include a variable representing the impact of continued technological development on yields, based on the historical growth in yields described above. Each model also includes variables representing the climatic variables — such as temperature and its impact on growing-degree days and killing-degree days — most important for each crop.

Table 1 shows what climate-related variables we modeled for each crop. For corn and soybeans, we focused on growing-degree days and killing-degree days. For winter wheat, we focused on fall freeze days, spring killing-degree days and spring precipitation. The result is that for each 4x4 km of agricultural land in Iowa, Minnesota and Kansas, we have a range of predictions — due to using a range of climate models — of likely future crop yields. Finally, we averaged these predictions at the county scale to make them more useful to farmers and policymakers.

TABLE 1:
Modeled results for each state and crop

Results	Iowa corn	Minnesota soybeans	Kansas winter wheat
Historical yield	x	x	x
2030 yield	x	x	x
2050 yield	x	x	x
Climate yield 2030	x	x	x
Climate yield 2050	x	x	x
Growing-degree days 2030	x	x	
Growing-degree days 2050	x	x	
Killing-degree days 2030	x	x	
Killing-degree days 2050	x	x	
Fall freeze days 2030			x
Fall freeze days 2050			x
Spring killing-degree days 2030			x
Spring killing-degree days 2050			x
Spring precipitation 2030			x
Spring precipitation 2050			x

[17] Van Wart, Justin, et al. "Estimating crop yield potential at regional to national scales." Field Crops Research 143 (2013): 34-43.

[18] Ray, Deepak K., et al. "Recent patterns of crop yield growth and stagnation." Nature communications 3.1 (2012): 1-7.

[19] Brisson, Nadine, et al. "Why are wheat yields stagnating in Europe? A comprehensive data analysis for France." Field Crops Research 119.1 (2010): 201-212.

[20] Chai, Yuan, et al. "Passing the food and agricultural R&D buck? The United States and China." Food Policy 86 (2019): 101729.

Agronomic impacts

The end-result of the analysis is a range of predicted crop yields for each county in Iowa, Minnesota and Kansas. Figure 3 illustrates what the range of predicted corn yields looks like for Tama County in central Iowa. The ensemble of 20 models predicts an average yield for the years prior to 2020 that closely tracks the actual historic yields from those years, which shows that the ensemble is giving realistic predictions. However, beginning in 2020, the models' yield predictions drop below the yields that would be anticipated if climate change wasn't a factor. The difference between the two becomes greater by mid-century, representing an increasing negative climate impact, or climate burden, on yields.

FIGURE 3:
Historic and projected corn yields in Tama County, Iowa

The climate burden on yield grows from a few bushels per acre in the 2010's to 22 bushels per acre by 2050.

How to interpret this graph: The dark blue line illustrates year-to-year fluctuations in historical corn yield based on yield data reported to USDA. The solid yellow-green line represents the historic trend in these reported yield data. The dashed yellow-green line represents projected improvements in future yields resulting from continued technological innovation and management improvements without any impacts from climate change. The gray shading shows the range in yield projections once climate change and its impacts are added in. It represents the range of possible future crop yields derived by combining (1) the assumed continuing linear trend of technological and management improvements (the dashed yellow-green line) with (2) projected yields derived from the Iowa corn crop growth model when that model is fed with predicted climate data for Tama County. The light blue line traces the average of these yield projections from an ensemble of 20 different models. Thus, the light blue line represents the range of projected crop yields for Tama County with continued technological development under an RCP4.5 warming scenario.

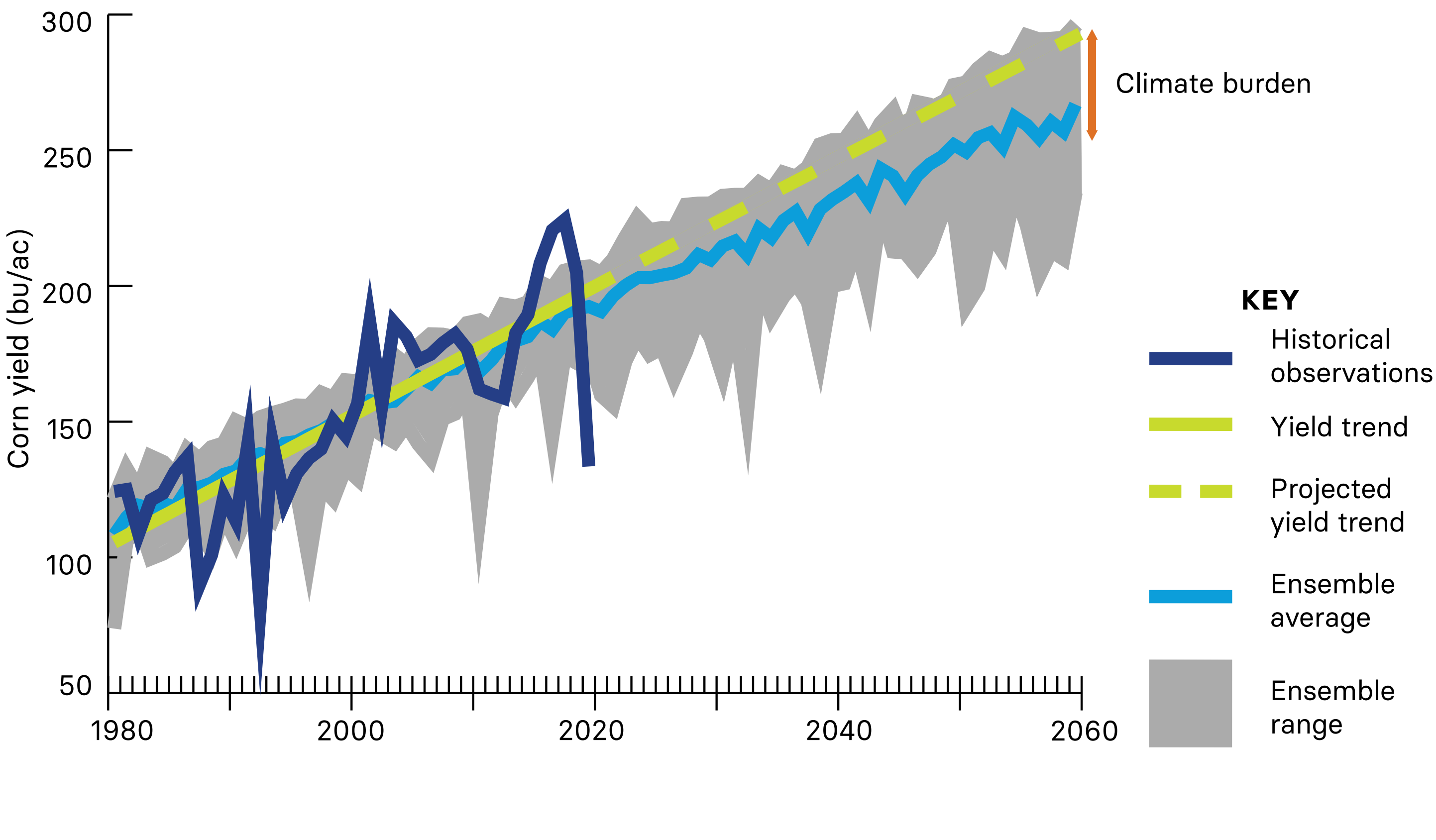
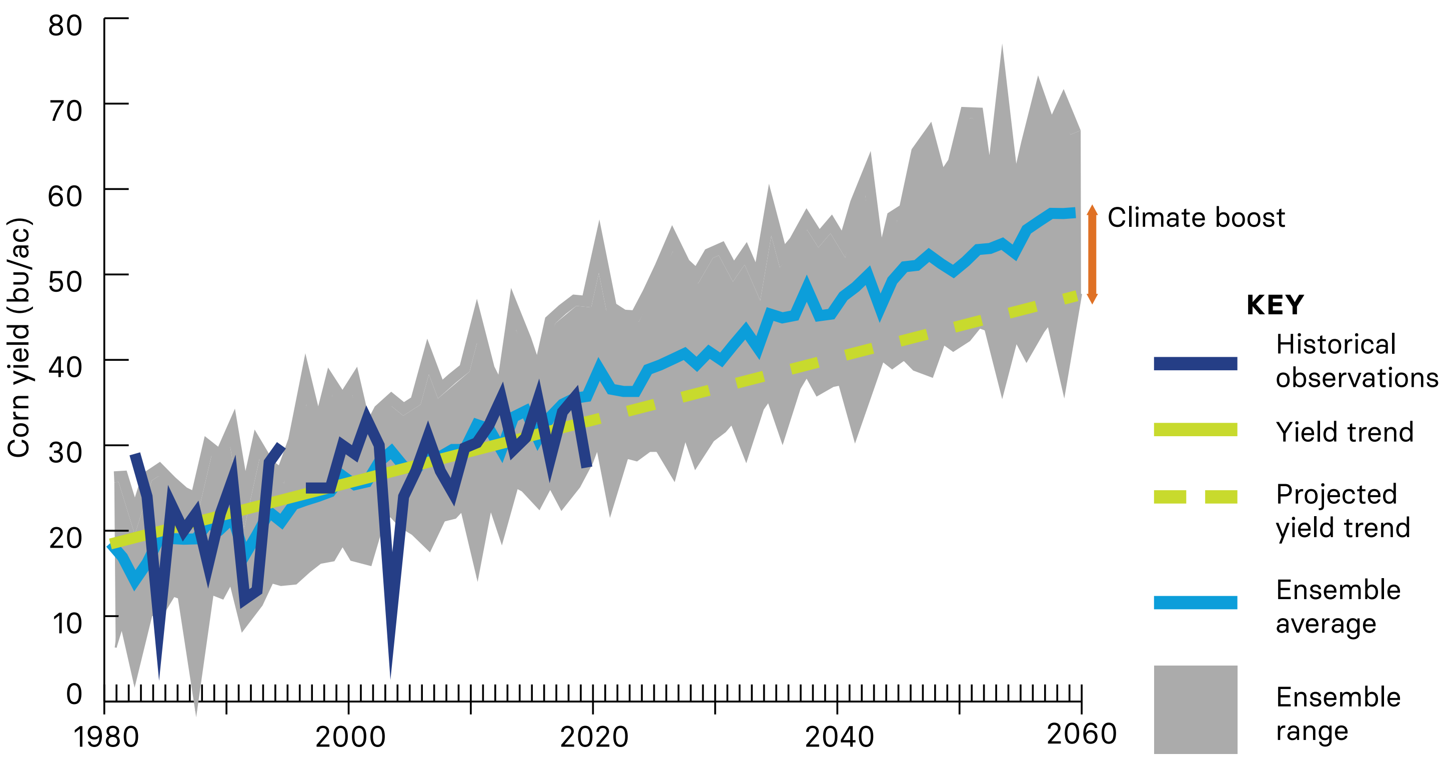


Figure 4 similarly shows the estimated soybean yields for Roseau County, Minnesota. In the years prior to 2020, the models predict yields that closely follow actual yields. However, beginning in 2020, the ensembles predict yields above what would be expected without climate change. The difference between the two becomes greater by mid-century, representing an increasing positive climate impact, or climate boost, on yields.

FIGURE 4:
Historic and projected soybean yields in Roseau County, Minnesota

How to interpret this graph: The dark blue line illustrates year-to-year fluctuations in historical corn yield based on yield data reported to USDA. The solid yellow-green line represents the historic trend in these reported yield data. The dashed yellow-green line represents projected improvements in future yields resulting from continued technological innovation and management improvements without any impacts from climate change. The gray shading shows the range in yield projections once climate change and its impacts are added in. It represents the range of possible future crop yields derived by combining (1) the assumed continuing linear trend of technological and management improvements (the dashed yellow-green line) with (2) projected yields derived from the Minnesota soybean crop growth model when that model is fed with predicted climate data for Roseau County. The light blue line traces the average of these yield projections from an ensemble of 20 different models. Thus, the light blue line represents the range of projected crop yields for Roseau County with continued technological development under an RCP4.5 warming scenario.



We focused primarily on the effect of changes in temperature, although warming will also increase plant water needs and decrease plant water availability.[21] That will further stress crops and likely lead to further declines in yield unless irrigation water is supplied. We have not looked at the likely impacts of climate change on future water use. Likewise, we did not attempt to model the impacts of extreme events, such as floods and droughts, which will become more frequent in the future.[22, 23] These events have the greatest impact on annual yields but are too difficult to predict years and decades in advance. It's likely, therefore, that our estimates of future yields are overly optimistic, and that climate impacts will be much greater than we present here.

This is important because all of our case studies show climate burdens for at least some parts of each state, and these predicted climate burdens increase from 2030 to 2050. If we made less- optimistic assumptions (Box 2), we would likely see much greater climate burdens over much larger areas of current crop production.

BOX 2:

Critical assumptions

We made three critical assumptions, each of which may lead to underestimates of the impact of climate on yields. First, we modeled a very conservative climate scenario, RCP 4.5, under which emissions would grow until mid-century and then decline. Based on countries' current GHG reduction pledges, this scenario is unlikely to be achieved, and greater climate impacts can be anticipated. Second, we assumed that technological innovation and improvements in management practices will continue at current rates. Declines in agricultural R&D spending suggest that this assumption may be incorrect. Third, we assumed that changes in temperature and temperature-related factors are the most important drivers of changes in yield. In making this assumption, we deliberately ignored other climate-related factors that are very difficult to model — extreme weather, droughts, floods, pests and diseases, and the availability of water for irrigation — and which may have substantial negative impacts on yields in certain years. Finally, we did not consider the potential impacts of other anthropogenic stresses — such as soil erosion and declines in soil fertility, or salinization of soils and groundwater — which will also negatively impact crop production.

[21] Grossiord, Charlotte, et al. "Plant responses to rising vapor pressure deficit." New Phytologist 226.6 (2020): 1550-1566.

[22] Seneviratne, Sonia, et al. "Changes in climate extremes and their impacts on the natural physical environment." A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) (2012): 109-230.

[23] Zhao, Cha, et al. "Frequency change of future extreme summer meteorological and hydrological droughts over North America." Journal of Hydrology 584 (2020): 124316.

Climate impacts on corn production in Iowa

Iowa is reliably the top producer of corn in the United States. It represents the heart of the U.S. Corn Belt, where corn farming is prevalent and highly productive. Flat or gently rolling topography combined with fertile soils make Iowa highly suitable for large-scale agriculture. Corn is cultivated in every county in Iowa and is only absent in highly urbanized areas and steep river valleys. Most of Iowa's corn production is rainfed, although a small amount of irrigation infrastructure exists north of Council Bluffs in western Iowa and near Muscatine in eastern Iowa.

Corn is an important staple cereal crop worldwide. For 4.5 billion people in developing nations corn, along with rice and wheat, provides at least 30% of food calories. In Central America and parts of Africa that value can be 20% for corn alone.[24] That makes it an important part of meeting rising nutritional needs and makes declining yields more concerning.

Climate change will drag down corn yield growth

Beneficial growing-degree days will likely increase due to climate change. Models predict that total growing-degree days will increase statewide by 11% by 2030 and 18% by 2050.

On the other hand, extreme heat, expressed as killing-degree days — cumulative days above 84°F (28.9°C), the temperature at which corn growth is inhibited — will also increase. Models estimate that state-average killing-degree days will increase by 57% by 2030 and 94% by 2050. Northern counties will see the largest jump in extreme heat.

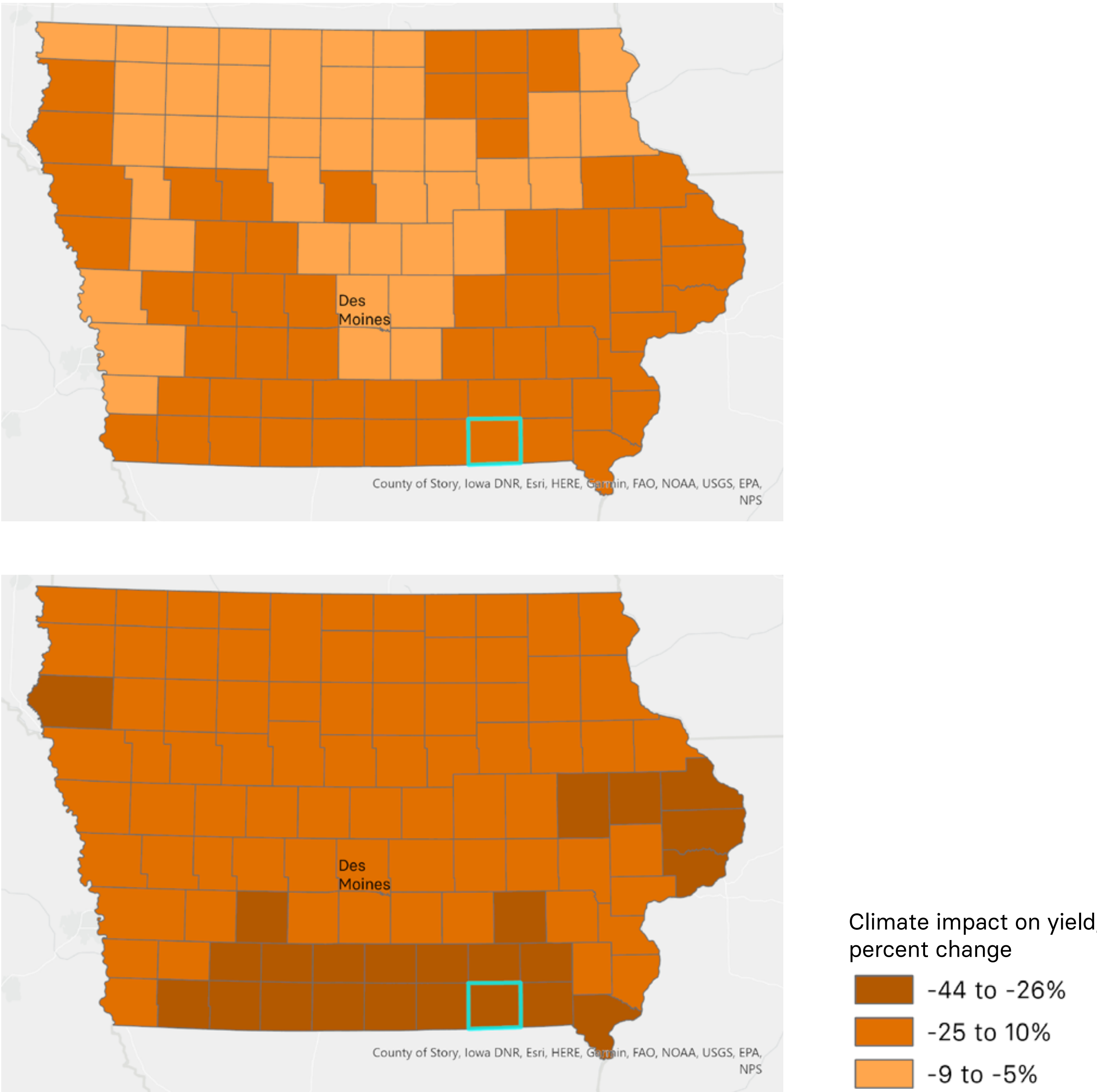
Corn yields will likely experience a climate burden throughout the state, but this is especially true in the southern counties. For example, driven by increases in extreme heat, the predicted climate burden on yields in Davis County is 25% in 2030 and 44% in 2050 (30 and 60 fewer bushels per acre, respectively). In other words, if not for climate change offsetting other productivity gains, yield per acre would be 30 bushels higher in 2030 and 60 bushels higher in 2050.

All counties will likely have climate burdens of 10% or higher by 2050. Figure 5 illustrates this increasing climate burden.

[24] Shiferaw, Bekele, et al. "Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security." Food security 3.3 (2011): 307-327.

FIGURE 5:
Climate impacts on corn yields in Iowa counties in 2030 and 2050

Maps for 2030 and 2050 show the percent change in corn yields due to climate change (i.e., the climate burden) in Iowa. Note that in all counties future yields are expected to experience climate burdens of 5% or more. Davis County is highlighted in blue.



Climate impacts on soybean production in Minnesota

Minnesota is consistently in the top three states for soybean production, with production concentrated in the western and southern portions of the state. Soybeans are mostly rainfed in Minnesota, although the state has more irrigation infrastructure than Iowa.

Soybeans are important to global food security due to their high protein and healthy fat content and low reliance on fertilizers. They can boost soil health through biological nitrogen fixation.[25] Soybeans are considered an affordable protein and a variety of foods can be made from them.[26] Their significance as an affordable source of protein makes declining yields troubling.

Climate change will make soybean yields highly variable by county

Growing-degree days will trend upward consistently, with the northern half of the state seeing the largest increases. Our models predict that total growing-degree days will increase statewide by 12% by 2030 and 20% by 2050.

However, extreme heat is also predicted to increase, especially throughout northern Minnesota. The entire state is estimated to have more killing-degree days during the growing season. Our models estimate that the state-wide average of killing-degree days will increase by 55% by 2030 and 105% by 2050.

Our research predicts that climate impact on soybean yields will be a mix of boosts and burdens (Figure 6). Some areas like Aitkin or Roseau Counties could see a climate-induced boost to yields due to more moderate temperatures. In some of the northern and central counties, extreme heat will create a significant climate burden.

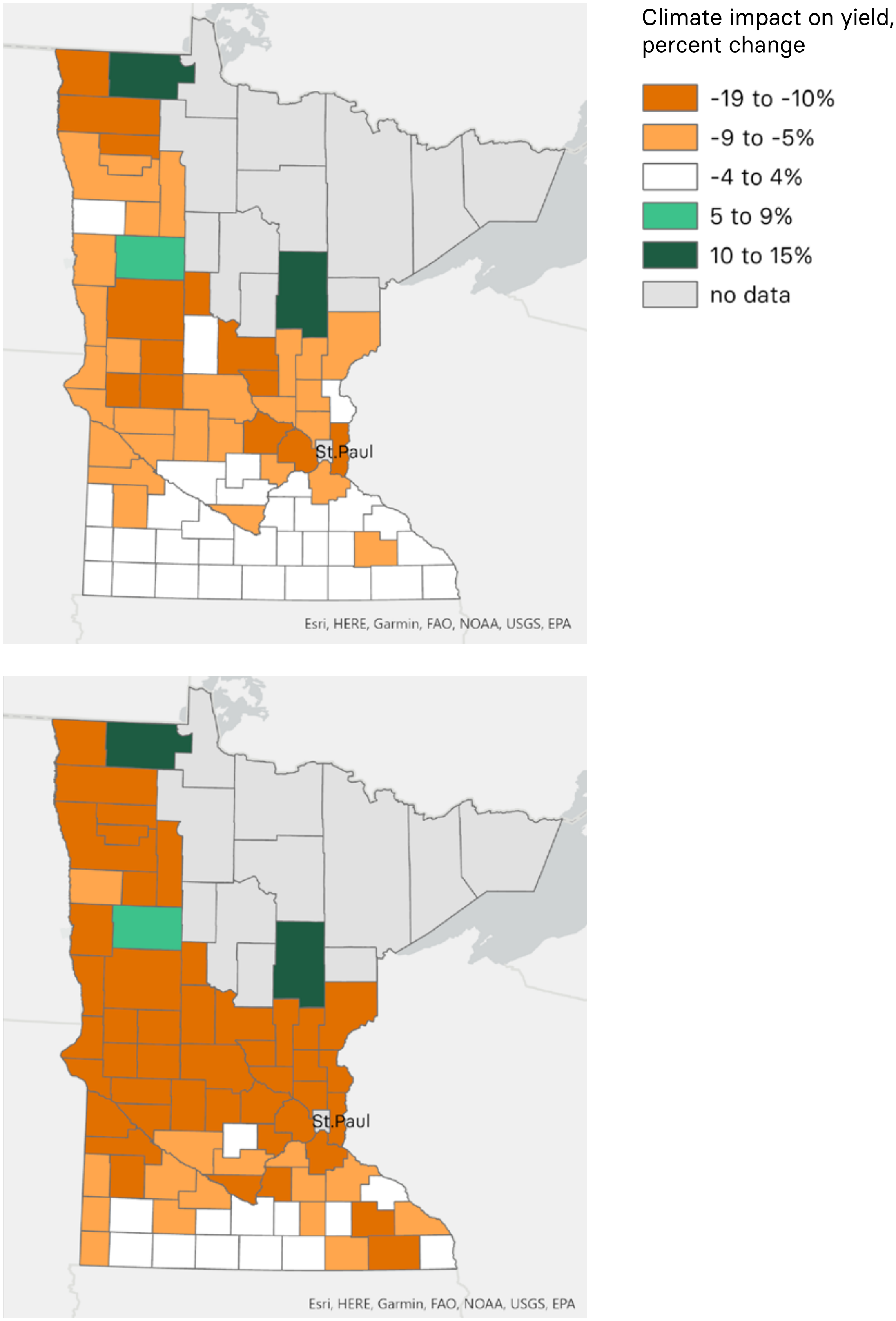
[25] Islam, Mohammad Sohidul, et al. "Soybean and Sustainable Agriculture for Food Security." (2022). https://doi.org/10.5772/intechopen.104129

[26] Messina, Mark. "Perspective: Soybeans Can Help Address the Caloric and Protein Needs of a Growing Global Population." Frontiers in Nutrition 9 (2022).

FIGURE 6:

Climate impacts on soybean yields in Minnesota counties in 2030 and 2050

Maps for 2030 and 2050 showing the percent change in soybean yields due to climate change (i.e., the climate burden) in Minnesota. Counties with dark and light shades of green may receive a climate boost. Counties in white might experience less than +/-5% change in yield as a result of climate change. Counties in dark and light orange may experience a climate burden.



Climate impacts on winter wheat production in Kansas

Kansas is by far the nation's top producer of winter wheat. Farmers plant winter wheat in the fall to take advantage of moisture in the fall and spring seasons and avoid the extreme heat of summer. Kansas has a highly variable climate, leading to large year-to-year swings in harvested area, yields and total production. Winter wheat acreage planted and harvested has declined slowly since a historical peak in the 1950s, but yields per acre have risen and overall production has remained stable.

Kansas slopes from west to east, and many of its soil and climate features follow a similar gradient. Winter wheat is planted throughout the state, but in recent years much of the historical acreage in the east has shifted to corn and soybean production. The western two-thirds of the state are semi-arid drylands where irrigation is used to ensure that crops receive the water they need.

Wheat is the most widely grown staple crop in the world, providing 20% of food calories consumed globally.[27] However, as the current wheat crisis has shown, the supply is unstable, and yields are stagnating in many places. Continual increases in yields will be necessary to ensure food security worldwide.[28]

Climate change will make winter wheat yields highly variable by county

Climate change will mean fewer fall freeze days throughout Kansas. The southeastern part of the state will see freeze days decline faster than the north. These changes could help to reduce freeze damage to winter wheat starts, potentially helping to increase yields. Our models predict that total fall freeze days will decrease statewide by 17% by 2030 and 23% by 2050.

Spring precipitation will tend to increase by both 2030 and 2050, benefiting winter wheat yields. Precipitation will increase the most in the eastern half of the state, though it's the semi-arid western portion of Kansas that needs it the most. On average across the state, spring precipitation will likely increase by 5% for both 2030 and 2050.

However, the rise of extreme heat in the springtime — killing-degree days in which daily average temperatures are above 82°F (27.8°C) — will be particularly detrimental to yields. These killing-degree days will increase by 2030 and even more so by 2050. Our models predict that total spring killing-degree days will increase statewide by 58% by 2030 and 96% by 2050. Exposure to extreme heat will likely have a more significant impact on wheat yield than any benefit from slightly more precipitation and reduced freeze damage.

The combined impact of these factors is that winter wheat yields are estimated to vary widely across the state (Figure 7). The eastern third of the state could see a consistent climate boost to wheat yields, while other parts of the state experience climate burdens, the severity of which will depend on complex interactions of soils, irrigation and climate change. From 2030 to 2050, eight counties in the central part of the state shift from experiencing relatively little climate impact to experiencing a climate burden of 5% or higher. Trego and Kingman counties in central Kansas show the largest climate burdens (16% and 10% respectively).

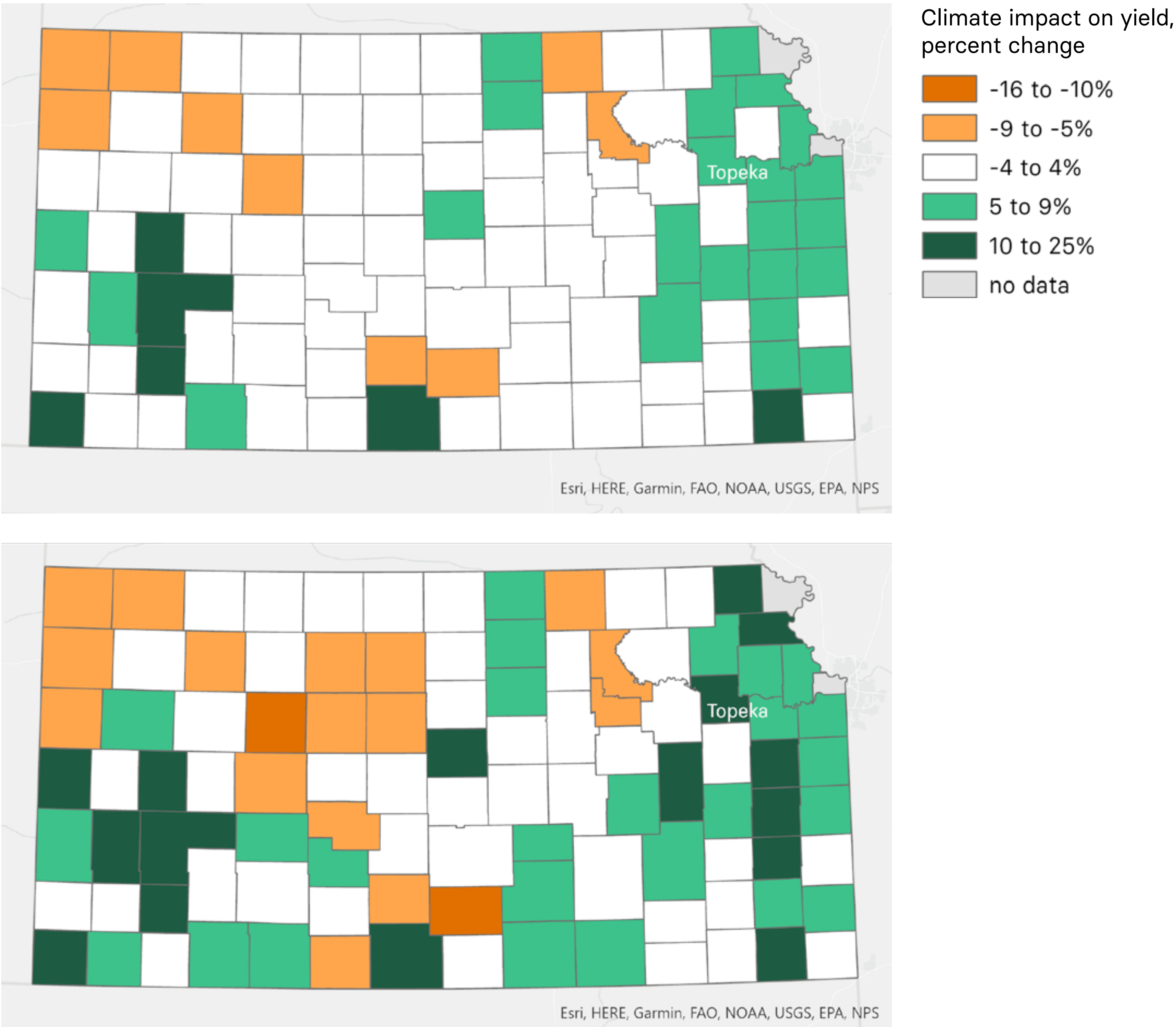
[27] Shiferaw, Bekele, et al. "Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security." Food Security 5.3 (2013): 291-317.

[28] "More wheat for global food security." 4 August 2022. https://www.morningagclips.com/more-wheat-for-global-food-security/. Accessed 7 September 2022.

FIGURE 7:

Climate impacts on winter wheat yields in Kansas counties in 2030 and 2050

Counties with dark and light shades of green may receive a climate boost. Counties in white might experience less than +/-5% change in yield as a result of climate change. Counties in dark and light orange may experience a climate burden. The counties in the darkest orange are Trego and Kingman.



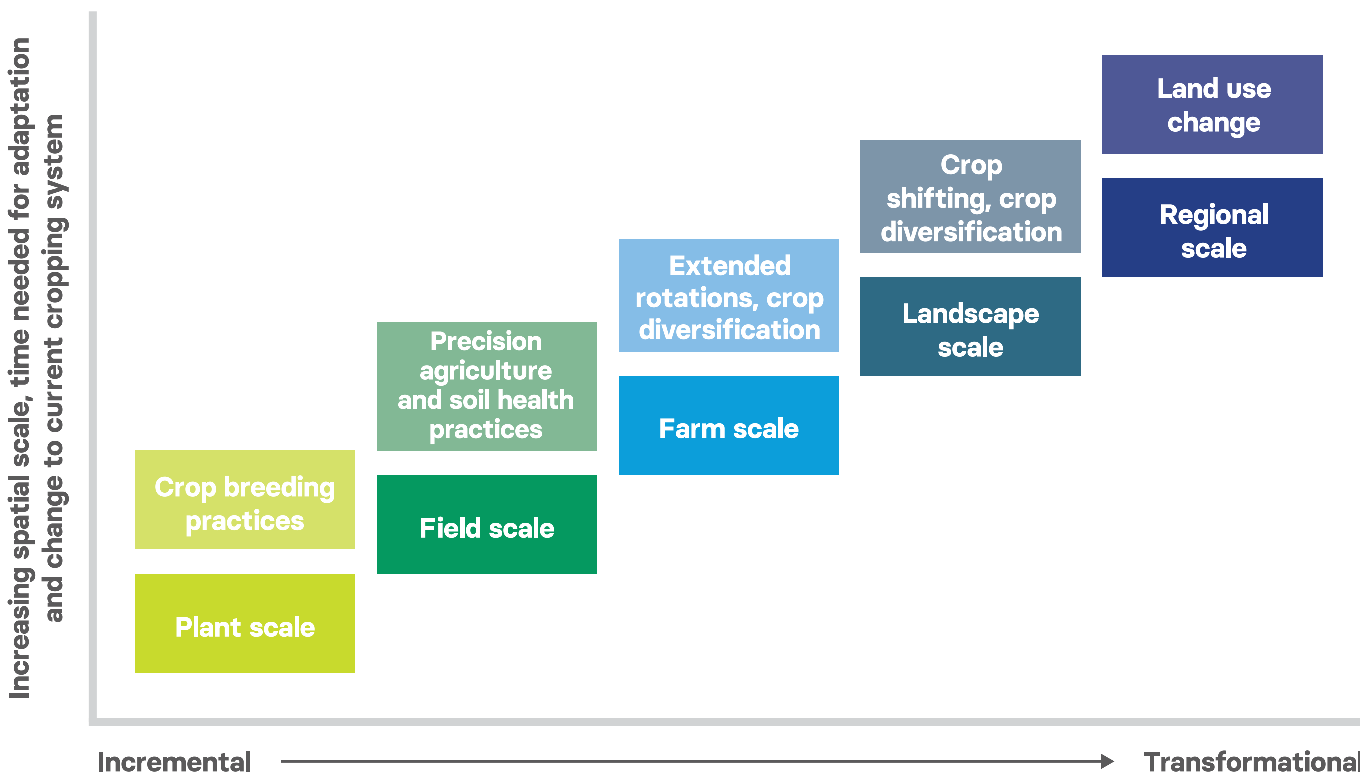
Adaptation opportunities

Incremental to transformational solutions

Adaptation opportunities range from incremental to transformational (Figure 8). Incremental changes modify the current cropping system. These changes are typically applied at the scale of an individual plant or a single crop field. In contrast, transformational changes are those in which the current cropping system is replaced by a different crop (crop-shifting), the mix of crops is diversified, or agricultural land is used to produce an alternative, non-cropping source of revenue. These changes typically take place at a landscape or regional scale.

FIGURE 8.
The spectrum of adaptation options.

In the figure below we show that moving along the spectrum from incremental to transformative change represents both an increase in the spatial scale at which change occurs (from the plant, to the field, farm, landscape and region) and an increasing degree of change from the current cropping system, meaning that increasing lead time is needed to make the change. We provide examples of the types of changes in crop selection, field management and land use that potentially increase resilience at each spatial scale.



We present the full spectrum of adaptation options because it is extremely difficult to determine what level of adaptation will be needed to respond to climate change at national and local levels. Most importantly, using a variety of approaches will make adaptation more successful. One thing which is clear is the need to avoid maladaptation. (See Box 3.)

BOX 3:

Maladaptation

Maladaptation occurs when actions taken to adapt to climate change backfire and make the situation worse. It typically happens when we focus on the short-term rather than the long-term, and when we look at only a piece of a problem instead of the larger system in which the problem occurs. In the cropping system context, some often-proposed “adaptations” turn out to be “maladaptations.” Two of the most common are proposals to reverse climate-induced yield declines through the addition of extra fertilizer or by switching from rainfed to irrigated agriculture. These apparent solutions, in fact, create additional problems: first, by requiring increased GHG emissions to create new fertilizer and to power irrigation pumps and, second, by locking farmers into a growing dependence on purchasing inputs of fertilizer or water that may grow more expensive – or even become unavailable – over time.

Three factors influence whether an incremental or transformational approach will be needed: uncertainty, risk and the limits to adaptation. Predictions of future climates can be quite different across the ensemble of 20 models used in our analysis. This makes it challenging to predict what cropping systems will be suitable for future climates. One model might predict a future climate that is not too different from the present, suggesting that an incremental approach to adaptation will be sufficient. Another model may predict a climate dramatically different from the present, for which transformative adaptation is needed.

Transformative adaptation may at first appear riskier than continuing with what works in the present. However, transformational adaptation will also take much longer to implement at scale than incremental adaptation. Therefore, there is also a risk that delaying action, with the hope of gaining more certainty over what the future climate will look like, can mean that it is too late to act by the time that the need for transformational adaptation becomes clear.

Another problem that contributes to uncertainty about whether incremental or transformative adaptation will be needed is the difficulty in quantifying the impact of different adaptation options.[29] Process-based models may be able to simulate the impact of changes in crop physiology resulting from improved genetics or management practices for a few staple crops, but they aren’t available for most crops. They also necessarily ignore other aspects of climate change that may greatly impact crop production. This prioritization of what to include and what to exclude in models has the unintended effect of spotlighting only a subset of climate impacts and is unlikely to show us the full impacts of climate change.[30]

There is a real risk that by focusing on what we can model, and ignoring what we can’t, we create an unwarranted bias towards incremental options. It may be that incremental changes are all we need — but there’s also a risk that by focusing on incremental changes we will miss the opportunity to invest in the more transformational changes that turn out to be necessary.

Additional complexity flows from the risk that current cropping systems may run up against adaptation limits, where there is no more adaptive capacity to support the current system. A hard adaptation limit means that further adaptation is not possible — a threshold has been reached, and the future system will look very different from the past system. A soft adaptation limit means there is no adaptation available now, but it could become possible with financial or technological support in the future.[31]

In reviewing potential adaptation options, we have followed the sequence outlined in Figure 8, from the most incremental to the most transformational change. We therefore begin by exploring innovative crop-breeding practices. Subsequently, we examine management changes at the field scale, in the form of precision agriculture and soil health practices. Finally, we consider switching from the current crop to an alternative crop or, in some cases, shifting agricultural land to an alternative, revenue-producing use.

[29] Corbeels, Marc, et al. "Can we use crop modelling for identifying climate change adaptation options?." Agricultural and Forest Meteorology 256 (2018): 46-52.

[30] Hertel, Thomas W., and Cicero Z. de Lima. "Climate impacts on agriculture: Searching for keys under the streetlight." Food Policy 95 (2020): 101954.

[31] Thomas, Adelle, et al. "Global evidence of constraints and limits to human adaptation." Regional environmental change 21.3 (2021): 1-15.

We note that, while there is a huge investment in crop-breeding approaches, it appears that breeding for a high tolerance to a specific set of conditions (e.g., heat-tolerance or drought-tolerance) reduces a cultivar's ability to cope with conditions other than those for which it is bred, meaning that while yields may be high in optimal years, yield variability will increase in sub-optimal years.[32, 33] Shifting to new cultivars is therefore risky if anticipated climatic changes do not materialize. In contrast, field management practices can be considered to be "no-regrets" options — changes that are likely to bring benefits regardless of climate change. We include in these "no-regrets" options various precision agriculture practices, which potentially reduce the need for external inputs such as fertilizer and water, thereby potentially offsetting the technology cost for farmers, while also reducing the environmental impacts of crop production. Other "no-regrets" options include the full suite of soil health practices, which help preserve soil fertility and can also help to reduce input costs for farmers.

For each of our case studies, we interviewed growers, experts from academia, nonprofit organizations and private companies in each state to identify adaptations that are already being adopted or are likely to be adopted in the coming decade. (See Appendix B for a list of interviewees.) We briefly review each adaptation option below and provide in Appendix C a set of resources for those wishing to learn more about specific options.

Whether incremental or transformational, the scale of change needed is likely to be immense. It's clear that investing in adaptation needs to begin now.

The range of adaptation options

Crop breeding practices

CRISPR genome editing

CRISPR genome editing involves modifying sub-gene sequences of the corn or soybean genome for crop improvement. CRISPR crops are regulated differently than transgenic crops in the U.S. (transgenic crops are typically regulated as genetically modified organisms, whereas CRISPR crops are not).

The first CRISPR corn variety has been approved for pilots in Iowa and is currently planted on an estimated 1,000 acres. By 2025, CRISPR corn is expected to increase deployment to 100,000 acres. Soybean genome mapping was completed in 2010, and scientists are still working on the gene-trait relationships. As a result, CRISPR for soybean has not been deployed in the field yet. There are several varieties developed in academic laboratories that will be planted on 10,000 acres in Minnesota by 2025.

Genomics-enabled hybrids

Genomics-enabled hybrids use gene mapping to identify desired traits from wild and uncommon wheat, corn and soybean varieties and introduce them into new hybrids. Mapping of the corn genome and identifying trait relationships has enabled the development of new hybrid crops throughout the past decade. An estimated 100,000 acres in Iowa grow genomics-enabled hybrid corn. By 2025, the area is expected to increase to 500,000 acres.

Developing hybrid soybean varieties takes longer because soybeans are self-pollinating. As a result, this technology is expected to be deployed to a lesser extent than hybrid corn. It was planted on 10,000 soybean acres in 2021 and will be on an estimated 100,000 acres by 2025 due to innovations in plant traits that improve hybrid development speed.

Desired traits — such as drought tolerance and high protein levels from wild or ancient varieties from the Middle East or Africa — are being incorporated into new wheat hybrids. This technology was deployed on 10,000 acres of Kansas winter wheat in 2021 and is projected to grow to 100,000 acres by 2025.

Precision agriculture practices

Variable rate technology

Variable rate technology uses sensors, soil maps and precision application equipment to vary the amount of fertilizer, seeds, water and other inputs within a field to reduce expenses and optimize applications. Reducing fertilizer application can reduce input costs and potentially generate new revenue streams (e.g., water quality credits) from nutrient reduction.

Currently, this technology is deployed on 500,000 acres in Iowa, which is 20% of its full potential. Deployment of variable rate technology in Iowa will increase to 1.5 million acres by 2025. The technology is currently deployed on 100,000 acres of Minnesota soybeans and is expected to grow to 500,000 acres by 2025.

[32] Lobell, D.B., Deines, J.M. and Tommaso, S.D., 2020. Changes in the drought sensitivity of US maize yields. Nature Food, 1(11), pp.729-735.

[33] Yu, C., Miao, R. and Khanna, M., 2021. Maladaptation of US corn and soybeans to a changing climate. Scientific reports, 11(1), pp.1-12.

Micro and drip irrigation

Micro and drip irrigation provides water conservation benefits to producers. Micro and drip irrigation in Kansas is particularly beneficial in the semi-arid western half of the state, where it represents an opportunity to move away from the more wasteful flood-irrigated wheat used today. Micro and drip irrigation is deployed on 500,000 acres of Kansas winter wheat in 2021 and is projected to expand to 1,000,000 acres by 2025.

Soil health practices

Soil health farming practices such as cover crops and conservation tillage lead to reduced erosion, improved soil moisture, more soil organic matter and improved water quality. These are applied to farming systems with the goal of soil conservation and rehabilitation.

The adoption of soil health practices is in part impacted by their profitability impacts on the farm. Reduced tillage is often associated with cost-savings by reducing fuel use, labor expenses, equipment repairs and depreciation.[34] Cover crops include added operating costs that can be offset in certain instances by input cost reductions (e.g., from fertilizer).[35] Cost savings often take a few years to materialize, which makes financial support including cost-share, warranty products and transition finance effective at supporting producers' adoption of cover crops.[36, 37]

Soil health practices in Kansas are anticipated to grow to 600,000 acres by 2025. Popular practices include planting forage cover crops such as rye following the harvest of wheat in Kansas. Iowa corn growers deployed cover crops on over 100,000 acres in 2021, and this area is likely to expand to 500,000 acres by 2025. Minnesota soybean growers have deployed cover crops to around 100,000 acres in 2021 and anticipate this area to expand to 500,000 acres by 2025.

Alternative crops

Alternative crops involve switching from current crops toward different crops that may be more adapted for the climatic conditions (e.g., more heat or drought-tolerant crops). This will become a more common adaptation as limits to adaptive capacity are reached. Improving crop diversity will be helpful for climate resilience. Several examples of alternative crops currently grown in Kansas are proso millet, canola, sunflowers, rye, triticale and oats.

Alternative land use

Alternative land use, or land repurposing, involves switching away from agriculture to land uses that may be more suitable for the current conditions and that can create new public benefits farmer revenue. In California, multi-benefit land repurposing represents an increasingly common adaptation in water-limited areas. It may become more common in Kansas as limits to adaptive capacity are reached. Examples of alternative land use include renewable energy leasing, conservation easements, well-managed rangeland, pollinator-friendly cover crops, habitat corridors, community parks, restored floodplains and dedicated groundwater recharge basins.

[34] Bowman et al. Conservation's Impact on the Farm Bottom Line. Environmental Defense Fund, KCoe Isom, Soil Health Partnership. 2021. https://business.edf.org/files/Conservation-Impact-On-Farm-Bottom-Line-2021.pdf. Accessed on August 24th, 2022.

[35] Sustainable Agriculture Research and Education. Cover crop economics: opportunities to improve your bottom line in row crops. 2019. https://www.sare.org/resources/cover-crop-economics/. Accessed on August 24th, 2022.

[36] Ibid.

[37] Monast, M. Financing Resilient Agriculture: how agricultural lenders can reduce climate risk and help farmers build resilience. 2020. https://business.edf.org/insights/how-agricultural-lenders-can-boost-climate-resilience/. Accessed on August 24, 2022.

Discussion

Implications of the agronomic impacts of climate change

Table 2 summarizes the predicted climate impact on yields across all three crops and states. The results show three clear takeaways:

1. Climate change impacts — expressed as climate burdens more than 5% and 10% — are already detectable by 2030 across our case studies. For example, by 2030, all counties in Iowa will likely experience a climate burden on corn greater than 5%, and 60% of counties will likely experience a climate burden of more than 10%.
2. Potential climate burdens are already quite large by 2030, with climate burdens potentially reaching as high as 25% for Iowa corn and 19% for Minnesota soybeans. To put these numbers in perspective, the 2012 drought in the U.S. Midwest led to declines of 25% in corn yields and production, declines of 9% in soybean yields and 5% in soybean production.[38] Thus by 2030, every year will see food production losses on the scale of the 2012 drought the 2012 drought.
3. While recent science has shown that climate impacts can be expected at the global scale by 2030,[39] this report is the first study to detail 2030 impacts on major U.S. cropping systems. Most importantly, the scale of impacts by 2030 suggests that we are rapidly running out of time to make the necessary adaptations.

TABLE 2
Climate burdens on yields by 2030 and 2050

State	% of counties with climate yield burdens greater than 5%, in 2030	% of counties with climate yield burdens greater than 5% in 2050	% of counties with climate yield burdens greater than 10% in 2030	% of counties with climate yield burdens greater than 10% in 2050	Highest climate burden on yields in 2030	Highest climate burden on yields in 2050
Iowa	100%	100%	60%	100%	-25%	-44%
Minnesota	56%	81%	17%	59%	-19%	-39%
Kansas	9%	17%	0%	3%	-9%	-16%

[38] Rippey, B.R., 2015. The US drought of 2012. Weather and climate extremes, 10, pp.57-64.

[39] Jägermeyr, Jonas, et al. "Climate impacts on global agriculture emerge earlier in new generation of climate and crop models." Nature Food 2.11 (2021): 873-885.

In all cases, the climate impacts are larger in 2050 than in 2030, as would be expected with increased warming. Our projected climate burdens are somewhat lower than those reported elsewhere. For example, researchers from Ohio State and Iowa State Universities[40] project climate burdens (which they refer to as "yield gaps") on corn of 25-37 bushels/acre by mid-century, larger than our estimate of 19 bushels/acre. As noted by these same researchers and others from Cornell University and Kansas State University,[41] the climate burdens projected for corn by the midcentury are comparable to and may even exceed the yield improvements resulting from the introduction of transgenic corn. This suggests that the level of technological innovation that will be needed to offset the impacts of climate change will be at least comparable to that required for the introduction of genetically engineered crops.

Given that public investment in agricultural R&D in the U.S. has declined[42] and the multiple decades required to bring innovations from concept to large-scale deployment, it is questionable whether the needed innovations will materialize in time. Of course, it's also possible to question whether the huge investments needed are best spent on technological innovation to sustain current cropping systems, or whether they might better be spent on facilitating transformative adaptation to cropping systems that are better suited to projected future climates.

The maps of the spatial distribution of climate burdens for each case study (Figures 5, 6 and 7) depict the high spatial variability in climate impacts at the county-scale. Within individual states, some areas may see a climate boost while others see a climate burden, and the intensity of the climate burden can vary tremendously, as shown in Figure 5 for corn production in Iowa. This suggests that investments in technology, technical assistance and other supports to help farmers adapt to climate change will need to be fine-tuned at small spatial scales.

Although we report on three specific case studies, if our results can be generalized to global agriculture, they hold significant implications for food security. In Figure 9 below, we again show Tama County, Iowa, which is one of the most productive crop-growing regions in the world. Even there, the climate burden on yields will make it extremely difficult to meet food production goals to help meet the projections of 50% more food needed for the nearly 10 billion people predicted to be alive by 2050.[43] Here we are using Tama County to be illustrative of the climate burden at the state, national and global scale.

The results would vary throughout farming regions and for different crops but, as the majority of crop-growing regions throughout the world are less productive than Tama County, Iowa, the challenge is clear. Even if technological innovation and management improvements continue at historic rates, which seems unlikely, the countervailing effects of climate change mean that it will not be possible to meet food production targets by 2050 without considerable adaptation efforts.

[40] Lee, Seungki, Yongjie Ji, and GianCarlo Moschini. "Agricultural innovation and adaptation to climate change: Insights from US maize." Journal of the Agricultural and Applied Economics Association (2022).

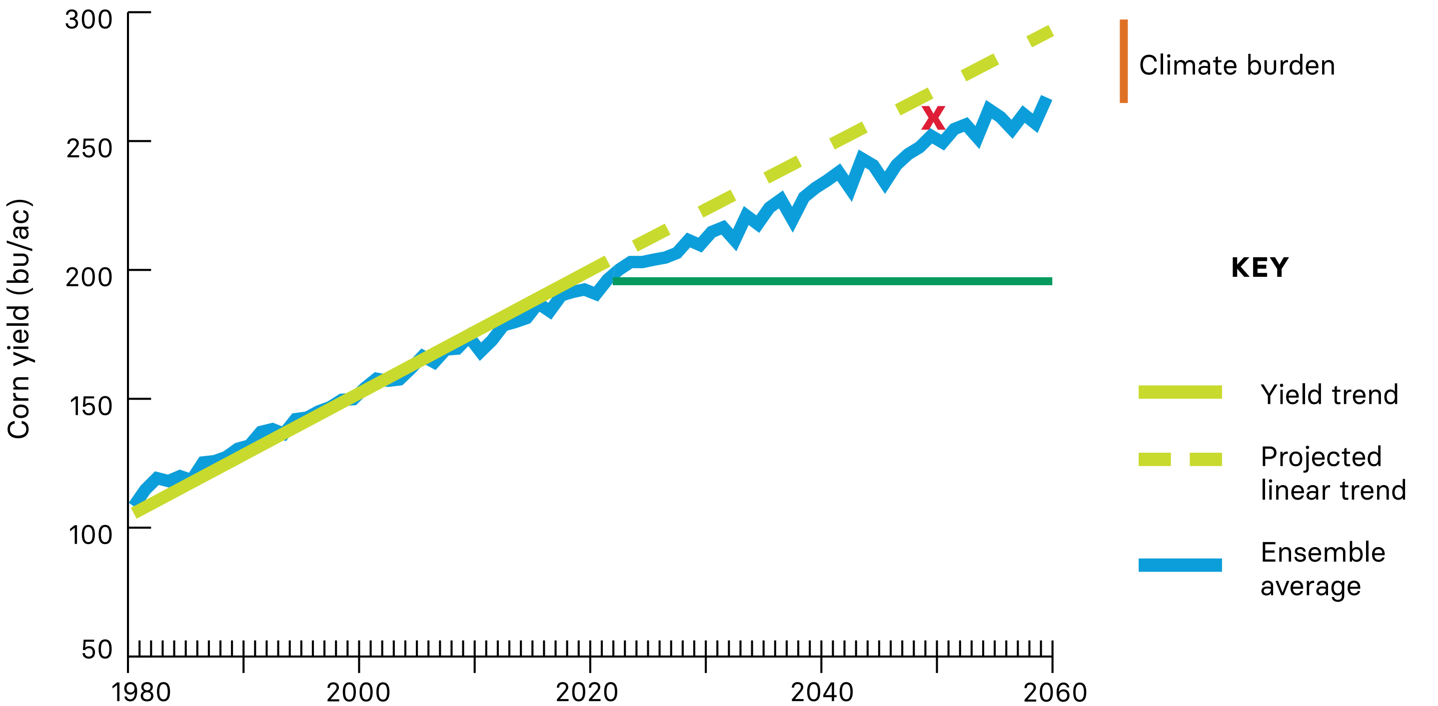
[41] Ortiz-Bobea, Ariel, and Jesse Tack. "Is another genetic revolution needed to offset climate change impacts for US maize yields?." Environmental Research Letters 13.12 (2018): 124009.

[42] Heisey, Paul, and Keith Fuglie. "Agricultural Research in High-Income Countries Faces New Challenges as Public Funding Stalls." Amber Waves: The Economics of Food, Farming, Natural Resources, and Rural America 2018.1490-2020-648 (2018).

[43] van Dijk, Michiel, et al. "A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050." Nature Food 2.7 (2021): 494-501.

FIGURE 9:
Projected yield shortage with and without climate impacts for the population in 2050

The red X indicates the increase necessary by 2050 in Tama County to increase food production by ~50%. The solid horizontal green line indicates that food production would remain at current levels without continued innovation and management improvements. The dashed yellow-green line shows the projected increase in food production expected from continued improvements in technology and management, without climate change. The solid light blue line indicates food production with climate change. Note that the red X indicating required food production lies above the blue line indicating attainable yields under climate change.



Looking ahead: Challenges and opportunities

Given the agronomic implications, it is critically important to create a strong support structure that will enable farmers and rural communities to adapt to climate change. The critical first step is to engage the broad agricultural community in a series of conversations about what climate change will mean for them, and how they can begin to prepare for it. These conversations need to bring scientists, food supply chain companies, agricultural lenders and farmer organizations together. The detailed, localized insights about the impacts of climate change that we provide in this report are essential to motivate local discussions and action. Otherwise, farmers — as "techno-optimists" — may be reluctant to take the actions that will be needed.[44] This type of information needs to be available for a broader range of crops and localities.

The negative impacts of climate on yields will threaten future food security, as shown in Figure 9. At the national level, conversations about agriculture and climate change focus primarily on the role that agriculture can play in climate mitigation. However, given the rapid pace of climate change, and the reality that it is already too late to avoid many of the negative impacts described in this report, policymakers, farmers and other agricultural decision-makers need to pay equal attention to climate adaptation and food security. Given the risks that short-term

[44] Gardezi, Maaz, and J. Gordon Arbuckle. "Techno-optimism and farmers' attitudes toward climate change adaptation." Environment and Behavior 52.1 (2020): 82-105.

actions taken to adapt to climate change (such as increasing irrigation use) can undermine climate mitigation efforts (leading to maladaptation), climate conversations must be more holistic if they are to avoid making things worse.[45, 46]

An integral part of preparing for climate change must be a better understanding of the effectiveness of a range of mitigation options. At present, huge sums of private sector R&D funding are directed toward developing new genetic technologies for corn. This is important but is unlikely to be a silver bullet for agricultural adaptation. The focus on corn has hindered the development of new genetic approaches for other crops, such as wheat (see Appendix C for research efforts underway). Perhaps even more important, we lack a clear understanding of whether the adaptation benefits resulting from genetic technologies will be adequate to address climate impacts of the scale predicted. It seems increasingly likely that they will not, and more transformative approaches, such as shifting to cropping systems better suited to future climates, will be needed.[47, 48] We call for new investment in R&D to help farmers and decision-makers understand the full suite of adaptation options, from incremental to transformational.

Finally, we note that climate change could increase the cost of current federal programs such as crop insurance. Producers purchase multi-peril crop insurance to reduce weather-related risks to their operations. They pay premiums commensurate to the amount of crop insurance coverage they purchase. The cost of the premiums is split between the producer and subsidies from the federal budget. USDA's Economic Research Service estimates that without adoption of climate adaptation measures, the cost of the Federal Crop Insurance Program could increase by over a third in the second half of this century.[49] This would increase the cost to taxpayers who pay roughly 72% of farmers' crop insurance premiums.[50] In addition, while insurance coverage is high for the major field crops, only one-quarter of U.S. agriculture's total production value is covered by crop insurance.[51] This means that the vast majority of U.S. agricultural production value is left unprotected by crop insurance and vulnerable to climate shocks.

Advancing solutions for the crop insurance program to integrate the risk-reduction value of adaptation measures is an opportunity to both reduce federal costs and help producers transition to climate-resilient agriculture practices. For example, removing federal crop insurance barriers to soil health practices will enable more producers to innovate with climate-adaptation measures.[52]

[45] Magnan, Alexandre K., et al. "Addressing the risk of maladaptation to climate change." Wiley Interdisciplinary Reviews: Climate Change 7.5 (2016): 646-665.

[46] Schipper, E. Lisa F. "Maladaptation: When adaptation to climate change goes very wrong." One Earth 3.4 (2020): 409-414.

[47] Hatfield, J. L., Lois Wright-Morton, and Beth Hall. "Vulnerability of grain crops and croplands in the Midwest to climatic variability and adaptation strategies." Climatic Change 146.1 (2018): 263-275.

[48] Vermeulen, Sonja J., et al. "Transformation in practice: a review of empirical cases of transformational adaptation in agriculture under climate change." Frontiers in Sustainable Food Systems 2 (2018): 65.

[49] Crane-Droesch, Andrew et al. (2019, July.) Climate change and agricultural risk management into the 21st century. U.S. Department of Agriculture Economic Research Service. Retrieved from: https://www.ers.usda.gov/webdocs/publications/93547/266.pdf?v=9932.1

[50] U.S. Government Accountability Office. 2014. Crop insurance: considerations in reducing federal premium subsidies. https://www.gao.gov/assets/gao-14-700.pdf. Accessed on August 24th, 2022.

[51] Calculated as the total crop insurance liability for 2017 (106,088,501,298) as a percentage of the value of agricultural production from the 2017 U.S. census of agriculture, ($388,522,695,000), which is 27.3%. Sources: Federal Crop Insurance Corporation. Commodity Year Statistics for 2017. Retrieved from: https://www3.rma.usda.gov/apps/sob/current_week/crop2017.pdf and U.S. Department of Agriculture National Agriculture Statistics Service. U.S. Agriculture Census, Table 2. Market Value of Agricultural Products Sold. Retrieved from: https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/ Volume_1,_Chapter_1_US/st99_1_0002_0002.pdf

[52] Agree. Crop Insurance Policy. https://foodandagpolicy.org/homepage/focus-areas/crop-insurance/crop-insurance-policy/. Accessed on 24 August 2022.

Conclusions

Our analysis (a "climate-optimist" scenario) has shown that predicted climate changes will create significant "climate burdens" on crop production as soon as 2030 for a variety of crops and locations. Yields will not increase at the same rate as they have in the past, even if we assume that technological and management improvements boost yields at the same rate as in the past.

In other words, we will be running just as hard but falling further and further behind in terms of overall food production. The levels of production needed to feed a growing population will remain unrealized.

We consider our estimated "climate burdens" to be an underestimate of likely impacts because we focused primarily on projected changes in seasonal temperatures and their implications for crop growth. We did not consider the impacts of pests and diseases, which are anticipated to worsen with warming temperatures, nor the expected increases in floods, droughts and other extreme weather events.

If GHG emissions are not reduced quickly, the planet is likely to follow a warming trajectory that is much more aggressive than the RCP 4.5 scenario we modeled, leading to much greater impacts on crop yields.[53, 54] Likewise, if rates of technological innovation stall — and the overall decline in public agricultural R&D spending suggests that they might — then much greater yield declines can be expected. Our results are in line with other studies of climate impacts on crop production, and our conclusions are robust, even for crops grown at higher latitudes. We initially expected that soybean production in Minnesota would benefit from a longer and warmer growing season, which would increase yields. However, our analysis suggests that while growing-degree days will increase, this benefit is outweighed by an even larger increase in killing-degree days, so that the anticipated "climate boost" is not realized.

Our analysis also shows the high spatial variability in climate impacts on yields, as shown by the maps of climate burden for Iowa and Kansas. (See Figures 5 and 7.) This spatial variability is likely to be critically important from the perspective of both food companies, which are likely to find some sourcing regions more affected than others, and of policymakers, who will need to consider regional and even local disparities in impacts when crafting policies to help farmers and rural communities adapt.

Interestingly, on the map of Iowa (Figure 5), we see that the greatest climate burden will be experienced in the most southern counties, a region which is already less productive for corn than the rest of the state. While our studies are insufficient to draw a general conclusion, they hint at the idea that crop production will be most affected in areas that are already comparatively struggling.

Fortunately, our research also uncovered some promising adaptation options that are already being implemented in our study areas. These options cover a spectrum from improved plant breeding to crop switching. Some adaptation options, such as adoption of management practices that improve soil heath,

[53] Rising, James, and Naresh Devineni. "Crop switching reduces agricultural losses from climate change in the United States by half under RCP 8.5." Nature communications 11.1 (2020): 1-7.

[54] Deryng, Delphine, et al. "Global crop yield response to extreme heat stress under multiple climate change futures." Environmental Research Letters 9.3 (2014): 034011.

are "no-regrets" options that are likely to benefit production regardless of climate change. Having a range of options is important because it creates the potential for an adaptive response, where the least disruptive approach can be deployed first, and more transformative options can be deployed later, as needed. However, planning for transformative approaches must begin long before they are needed because this type of adaptation requires a much longer lead time than incremental approaches do.

We note a number of challenges and opportunities for successful adaptation to climate change. First, we note the need to better integrate discussions of climate adaptation with those of climate mitigation and to bring diverse stakeholders in the agricultural community and food supply chain together to begin to plan now for the adaptation that will be needed in less than a decade. Secondly, we suggest a more comprehensive and strategic approach to agricultural R&D that will allow identification of a broader suite of adaptation options for many more crops than at present. Additionally, we suggest changes to the Federal Crop Insurance Program to reduce barriers to adaptive practices and provide tailored risk management products that support producers adopting these practices.

The analyses documented in this report suggest a need for urgent, cross-sectoral and multi-scale dialog about the best ways to prepare for the climate change that is now inevitable. In writing this report, we have become deeply concerned about the potential impacts to rural community viability and food security if no action is taken. At the same time, we have been inspired by the farmers and researchers who are developing solutions that point towards a more resilient future for U.S. agriculture. We hope that this report serves as a catalyst for change that brings the work of these farmers and researchers to the forefront of decision-making.

Appendix A: Methodology

Data sources

To explore climate impacts on U.S. agriculture, we collected publicly available county-level agronomic data such as crop yield, harvested area, and total production from the USDA.[55] We collected hydrologic data such as irrigation area and groundwater recharge from the U.S. Geological Survey.[56, 57] We collected climate data, such as temperature and precipitation, from the PRISM group at Oregon State University and the Climatology Lab at the University of California Merced.[58, 59] Historical observations span the years 1981 through 2020 with daily time resolution. This allowed us to capture recent crop improvements, climate variability and crop-climate relationships. We studied downscaled climate model output from 20 climate models produced by 13 climate research centers. These climate projections have daily time resolution and span the years 1981 through 2060. This range includes the historical period, the near-term we are living through now, and the mid-century time frame that policymakers often use as a target. Thus, we refer to the forty-year period centered on 2000 as "historical," the twenty-year period centered on 2030 (2021 through 2040) as "near-term," and the twenty-year period centered on 2050 (2041 through 2060) as "mid-century."

Climate scenarios

We cannot know the future precisely, however scenarios allow us to explore possible futures. To create climate scenarios, economists and technologists first construct plausible time series of socioeconomic climate drivers such as population, technology development, education and land use. These pathways each result in different levels of GHG emissions, cumulative GHG concentrations in the atmosphere and global radiative forcing. These timelines are referred to as representative concentration pathways (RCPs) and grouped by their end-of-century global average radiative forcing (e.g., RCP4.5 is +4.5 watts per square meter). This represents Earth's energy imbalance, which is the physical driver of global warming.

For this study, we considered climate simulations following RCP4.5, a middle-of-the-road scenario where GHG emissions peak before mid-century and then slowly decline (Figure 10). RCP4.5 results in a global average warming of about 2.4°C (4.3°F). We extracted data for crop-specific regions of the three U.S. states from 20 climate model simulations following RCP4.5. We could have chosen a scenario with larger forcing, like RCP6 or RCP8.5. RCP6 is characterized by increasing emissions through mid-century, then a slow decrease and stabilization by 2100. RCP8.5 is characterized by ever-increasing emissions through 2100. In other words, things could be worse than the scenario we chose. However, energy modelers have argued that RCP8.5 is inappropriate for near-term emissions and that development trends and international commitments have put the world on a path more like RCP4.5.[60, 61]

[55] National Agricultural Statistics Service, Row Crops: https://www.nass.usda.gov/

[56] Pervez MS and Brown JF, 2010 Mapping Irrigated Lands at 250-m Scale by Merging MODIS Data and National Agricultural Statistics. Remote Sensing 2 2388-2412 https://doi.org/10.3390/rs2102388; MIrAD-US: https://doi.org/10.5066/P9NA3EO8

[57] Flint LE and Flint AL 2014 California Basin Characterization Model: A Dataset of Historical and Future Hydrologic Response to Climate Change (ver. 1.1, May 2017) U.S. Geological Survey Data Release https://doi.org/10.5066/F76T0JPB

[58] PRISM Climate Group at Oregon State University https://prism.oregonstate.edu/

[59] Climatology Lab at UC Merced https://www.climatologylab.org/maca.html

[60] Hausfather Z and Peters G 2020 RCP8.5 is a problematic scenario for near-term emissions Proc. Nat. Acad. Sci. USA 117 27791–27792 https://doi.org/10.1073/pnas.2017124117

[61] Pilke Jr R, Burgess M, and Ritchie J 2022 Plausible 2005–2050 emissions scenarios project between 2° and 3° of warming by 2100 Environ. Res. Lett. 17 https://doi.org/10.1088/1748-9326/ac4ebf

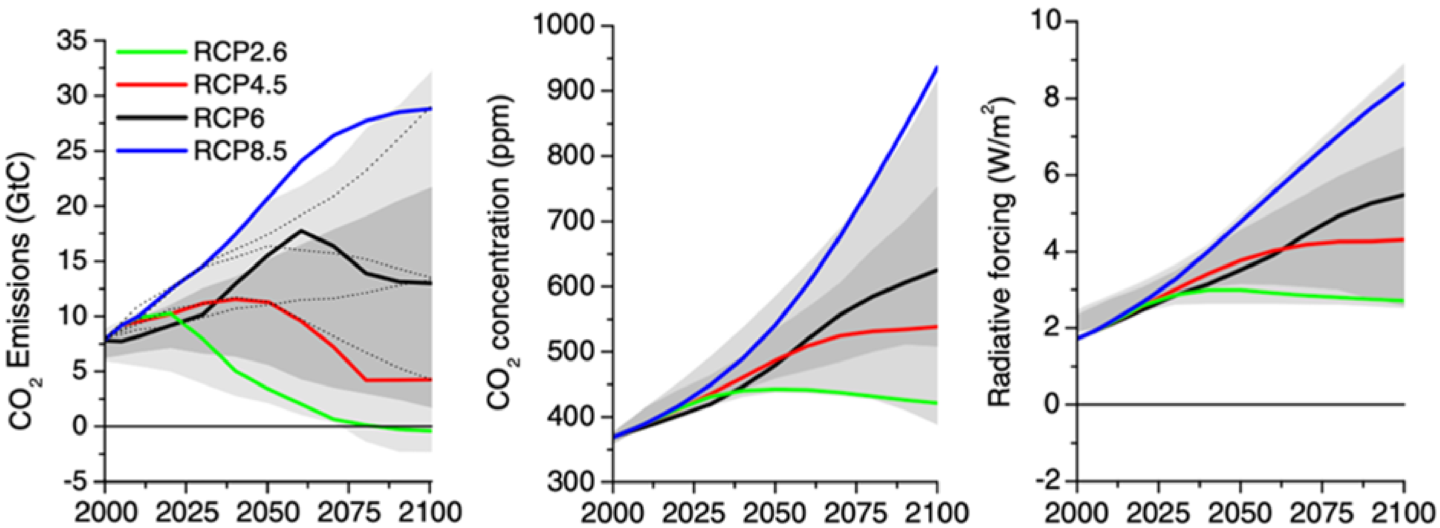


FIGURE 10:

RCP scenarios' impact on CO_2 emissions, atmospheric CO_2 concentrations and radiative forcing

CO_2 emissions (gigatons, left), atmospheric CO_2 concentrations (parts per million, center), and radiative forcing (watts per square meter, right) under four RCP climate scenarios. Adapted from van Vuuren et al.

Historical climate data

This study uses historical climate data from the PRISM and the gridMET datasets. PRISM uses a digital elevation model and regression-based statistical framework to estimate gridded climate fields from station data.[62] For example, with precipitation, it relies on the observation that orographic influences cause precipitation to increase with elevation. The PRISM model considers topographic facets when grouping relevant nearby stations. This produces lower errors compared to those other geostatistical tools. The resulting datasets incorporate a variety of modeling techniques and are available at multiple spatial/temporal resolutions, covering the period from 1895 to the present.

gridMET is a dataset of daily high-spatial resolution (~4-km, 1/24th degree) surface meteorological data covering the contiguous U.S. from 1979 through present day.[63] gridMET was developed to produce daily and subdaily fields at a time when PRISM was only available for monthly and annual time scales. gridMET provided this higher resolution using climatologically aided interpolation. While climatologically aided interpolation typically superimposes interpolated station anomalies with climatological normals to estimate monthly time series, gridMET superimposes interpolated daily departures of monthly averages from NLDAS-2 (reanalysis) with monthly data from PRISM.

Future climate projections

The Multivariate Adaptive Constructed Analogs, or MACA, dataset was used for future climate projections.[64] MACA uses daily data from global climate models and historical observations. Global models produce data at high spatial scales that do not allow a county-by-county analysis. MACA downscales the data using a statistical method. These statistical methods contrast with so-called dynamical methods, which rely on regional climate models nested in a global climate model. Dynamical downscaling suffers from biases introduced by the driving global climate model and computational intensity. Statistical downscaling is comparatively computationally efficient, yet it has limitations associated with the assumption of stationarity and questionable fidelity to some first principles of meteorology. The MACA data set consists of output from 20 global climate models (GCM) produced by 13 climate research centers. The model skill, or the ability to replicate the Earth's climate, varies over space, time and across the

[62] Daly C, Neilson RP, and Phillips DL 1994 A statistical-topographic model for mapping climatological precipitation over mountainous terrain J. Appl. Meteor. 33 140–158 https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2

[63] Abatzoglou J T 2013 Development of gridded surface meteorological data for ecological applications and modelling Int. J. Climatol. 33 121–131 https://doi.org/10.1002/joc.3413

[64] Abatzoglou J T and Brown T J 2012 A comparison of statistical downscaling methods suited for wildfire applications Int. J. Climatol. 32 772–780 https://doi.org/10.1002/joc.2312

multi-model ensemble. To communicate the range of expected outcomes, we calculated multi-model minimum, maximum, mean and flagged outlier models.

Outlier analysis was completed at the county level for near and medium future changes. Near future change is defined as the difference between the 2021 to 2040 mean and the 1981 to 2020 mean. Medium future is defined as the difference between the 2041 to 2060 mean and the 1981 to 2020 mean. We assumed the variation in output at the county level across the 20 models followed a normal distribution. Models that predicted a change in variable that was greater than or less than three standard deviations from the multi-model mean were flagged as outliers. Outliers were not removed from the analysis since removing the outliers would result in an inconsistent number of models in the calculation of each multi-model mean and an inconsistent number of models included in the agronomic modeling.

The county level output for each model as well as the calculation of the multi-model minimum, mean, maximum and standard deviation are shown in the "Climate Data" Excel spreadsheets for each state that are provided on EDF's website. Models with a change in climate parameter that is more than three standard deviations above the mean are flagged in pink. Models with a change in parameter that is more than three standard deviations below the mean are flagged in blue.

In the Iowa analysis, the HadGEM2-ES model produced near future changes in killing-degree days that are greater than three standard deviations from the mean. The MRI-CGM3 model produced a near future change in freezing days for a Kansas county that was greater than three standard deviations above the mean. For Minnesota, the GFDL-ESM2G model produced near-future vapor pressure deficit changes that were more than three standard deviations below the mean.

Localization

Rather than average climate data over the entire area of each county, we implemented a weighted average using historical crop growing area. In other words, we produced a county average by up-weighting the areas with more intensive crop growing and down-weighting the areas with little or no crop growing, like urban areas and inland waters (e.g., lakes and rivers). This is arguably better than averaging all of the gridded data for a county together, particularly for large counties with mixed land-use or a large fraction of inland waters.

The weighting scheme was implemented as follows. First, we developed historical crop growing baselines for each use case. These were determined from USDA CropScape maps with 30-meter resolution.[65] For each 30-meter grid cell in each state, we determined the crop frequency from 2011 to 2020. Then we computed the fraction of each 4-km climate data grid cell with any corn cultivation from 2011 to 2020 (crop frequency>0). An example of this crop area fraction for Iowa corn is shown in the left panel of Figure 11. Then for each county, we computed grid cell weights by dividing each grid cell's crop area fraction by the sum of the crop area fractions within the county. Finally, crop area-weighted county climate data were formed for each climate variable with the gridded climate data and gridded crop area weights.

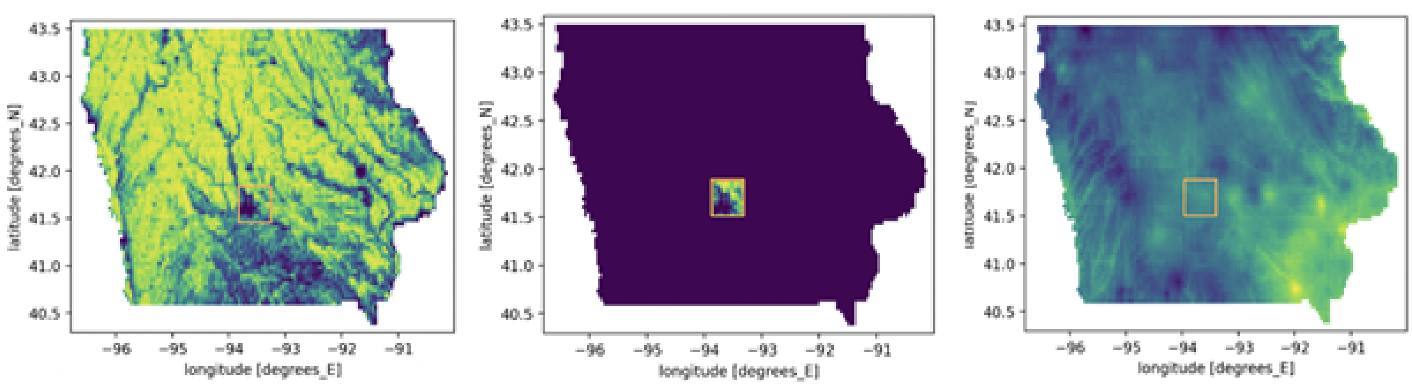


FIGURE 11:
Illustration of the weighting scheme based on crop frequency

Fraction of 4,000-acre grid cells with corn cultivation 2011-2020 (left), corn area weights for Polk County, Iowa (center), and maximum temperature for January 1, 1981 (right). Polk County, Iowa, border is in indicated across all three. The Polk County corn area-average for January 1, 1981 of 31.9°C is generated by weighting the grid cells on the right panel by the weights in the center panel.

[65] USDA CropScape https://nassgeodata.gmu.edu/CropScape/

Agronomic modeling

It is often taken for granted that weather and climate are dominant factors in crop yield outcomes. Indeed, average climate conditions set the geographic range that rainfed crops can be cultivated. For example, depending on its relative maturity corn requires 1,600 to more than 2,500 growing-degree days accumulated over the growing season. This limits its northern range or forces growers to choose shorter relative maturity varieties. In terms of water, crops have minimal water requirements that are typically met through precipitation. In some drier climates, supplemental irrigation can help overcome minimal growing season precipitation. When the average climate changes, farmers can adaptively take advantage of the shifting conditions and the geographic range of crops shifts.[66]

Weather and climate variations on timescales of days to years also influence crop yields. Year-to-year variations in growing-degree days, extreme heat, precipitation and other climate metrics are correlated with yields. Lobell and Field used linear regression to show that growing season temperature and precipitation measures account for approximately 30% of year-to-year variability in global-average grain yields.[67] Statistical methods of associating climate and yield variability are common in the peer-reviewed literature and compare favorably with process-based models.[68]

In this study we developed a set of historical agronomic data spanning 1981 through 2020 from public sources and defined a baseline historical yield using the years 2011 through 2020. These serve as inputs to the crop-climate impact modeling.

Model specification

For each use case, we specified a linear regression model with predictors representing agronomic and climatic variables to project crop yield. As described in the introduction, we considered an adaptation scenario where yields continue to follow a historical linear trend and a no adaptation scenario where yields continue to follow a historical trend while heightened or hindered by climate change. The adaptation scenario models yield using a time trend only. In other words, we fit a linear trend to historical crop yields 1981 through 2020 and project it forward through 2060. The no adaptation scenario models yield using a time trend plus additional predictors that account for climate influences unique to each state-crop-use case. For the sake of brevity, we describe each model briefly and include footnotes linking to original sources.

Iowa corn and Minnesota soybeans

We followed Butler and Huybers's model specification for Iowa corn and Minnesota soybeans.[69] Their model includes a time trend term to account for technology improvements, a growing-degree days term to account for the positive influence of optimal temperatures, and a killing-degree days term to account for the negative influence of extreme temperatures. The climate variables were averaged over a fixed growing season from May through October. The model accounts for 40-to-60% of year-to-year variations in county-level crop yields. The model incorporates some precipitation effects indirectly through its influence on temperature (i.e., wet years tend to be cool years and dry years tend to be hot years). The model does not account for extreme precipitation, flooding or wind damage associated with severe convective storms.

Kansas winter wheat

We followed Jesse Tack and colleagues for our model specification of Kansas winter wheat.[70] Their model includes a time trend term to account for technology improvements and a series of three-month average climate variables corresponding to fall, winter and spring. Rather than implement their full model with >16 predictors, we implemented a more parsimonious model with only the four most significant predictors: fall freeze days, spring killing-degree days and two spring precipitation terms (linear and quadratic). Fall freeze days and spring killing-degree days are negatively correlated with yield (i.e., fewer are better). Spring precipitation in the average (i.e., linear term) is positively correlated with yield. In the extreme (i.e., quadratic term), spring precipitation is negatively correlated with yield. The model accounts for 20-to-40% of year-to-year variations in county-level winter wheat yields. The model does not account for wind damage associated with severe convective storms nor does it account for irrigation, since the input crop yield data combines rainfed and irrigated winter wheat.

[66] Sloat LL, Davis SJ, Gerber JS, Moore FC, Ray DK, West PC, and Mueller ND 2020 Climate adaptation by crop migration Nature Comm. 11 https://doi.org/10.1038/s41467-020-15076-4

[67] Lobell DB, and Field CB 2007 Global scale climate-crop yield relationships and the impacts of recent warming Environ. Res. Lett. 2 https://doi.org/10.1088/1748-9326/2/1/014002

[68] Lobell DB, and Asseng S 2017 Comparing estimates of climate change impacts from process-based and statistical crop models Environ. Res. Lett. 12 https://doi.org/10.1088/1748-9326/aa518a

[69] Butler EE, and Huybers P 2013 Adaptation of US maize to temperature variations Nature Clim. Change 3 68–72 https://doi.org/10.1038/nclimate1585

[70] Tack J, Barkley A, Lanier Nalley L 2015 Effect of warming temperatures on US wheat yields Proc. Nat. Acad. Sci. USA 112 https://doi.org/10.1073/pnas.1415181112

Appendix B: Interviewees

Interviews

Our analysis was enabled by interviews with experts. We interviewed the following individuals, grouped by case study:

Iowa corn

- Dr. David Ertl, Iowa Corn Growers Association.
- Dr. Dermot Hayes, Iowa State University.
- Dr. Jennifer Hsiao, University of Washington.
- Dr. Soo-Hyung Kim, University of Washington.
- Dr. Giancarlo Mohschani, Iowa State University.
- Mr. Ben Riensche, Blue Diamond Farms.
- Dr. Patrick Schnable, Iowa State University.

Minnesota soybeans

- Dr. Abigail Swann, University of Washington.
- Dr. Tracy Twine, University of Minnesota.

Kansas winter wheat

- Dr. Allan Fritz, Kansas State University.
- Mr. Justin Knopf, Knopf Farms.
- Dr. James Schnable, Dryland Genetics.

Appendix C: Adaptation resources

Alternative crops

- The Noble Research Institute has documented several leading alternative crops for winter wheat — canola, sesame, sorghum and sunflowers — as part of its farmer education program. The institute also has a genetic marker-assisted breeding program for small grains, such as rye, oats and triticale.[71]
- Kansas State University conducts pilot projects and develops production economics sheets for alternative crops such as canola and field peas.[72]

Alternative land use

- The Kansas Forage and Grassland Council works with farmers and ranchers to encourage the conversion of cropland to pastureland and row crops to forage crops.[73]

CRISPR genome editing

- Professor Wang of Iowa State University has introduced a fast-flowering variety of corn using CRISPR/Cas-9.[74]
- Professor Stupar of the University of Minnesota researches soybean molecular genetics, particularly, the genetic basis of natural and induced variation in the crop and CRISPR editing for trait improvement.[75]
- Professor Jacobs of the University of Georgia developed a CRISPR system and has shown it to be effective in soybeans by knocking out a green fluorescent protein transgene and modifying nine endogenous loci.

Genomics-enabled hybrids

- The 10+ Wheat Genome Project is an international research effort, including Kansas State University, to capture the complexities of the wheat genome. Doing this will empower easier genetic modification of wheat to improve crop quality, harvests and resilience. The consortium has introduced 13 cultivars through collaborative research including a recent introduction of a hybrid based on wild emmer wheat from Israel and Lebanon with high drought tolerance and protein content.[76]
- Cornell University scientists specialize in wheat genomics resistance to stem, yellow and leaf rust. Professor Frank has manipulated floral traits in soybeans to make the flowers more attractive to pollinators.[77]
- The International Maize and Wheat Improvement Center has characterized 80,000 varieties of wheat and is recognized by peer scientists as the largest genotyping undertaking for wheat.[78]
- The Israeli Plant Gene Bank stores more than 4,000 varieties of wild wheat such as wild emmer and early domesticated varieties that are no longer in commercial production.[79]
- The Ethiopian Biodiversity Institute stores and studies more than 285 wild and cultivated varieties of Ethiopian durum wheat.[80]
- The Brazilian Agricultural Research Corporation uses marker-assisted selection and breeding for corn.[81]
- The Maize Genetics and Genomics Database is a nonprofit organization that, using funding from USDA, has created an opensource data base that is searchable for specific genes, proteins, metabolic pathways, RNA sequence expressions. The database also includes a library of known mutant phenotypes and diversity of genotypes.[82]
- Professor Wang from Iowa State University recently won a grant from the National Science Foundation to study the genetic diversity of corn, including the tropical maize germoplasm, in collaboration with the University of Hawaii.[83]

[71] noble.org

[72] https://www.agronomy.k-state.edu/extension/crop-production/canola.html and https://www.northwest.k-state.edu/agronomy/fieldpeas.html

[73] ksfgc.org

[74] McCaw, Morgan E., et al. "Development of a transformable fast-flowering mini-maize as a tool for maize gene editing." Frontiers in genome editing 2 (2021): 622227.

[75] Liu, Junqi, et al. "Genome editing in soybean with CRISPR/Cas9." Plant Genome Editing with CRISPR Systems. Humana Press, New York, NY, 2019. 217-234.

[76] https://10wheatgenomes.com/

[77] soybeanresearchinfo.com/research-highlight/re-engineering-the-soybean-flower-to-capture-hybrid-vigor/

[78] nature.com/articles/s41467-020-18404-w

[79] igb.agri.gov.il/web/?lang=en&page=47

[80] ebi.gov.et

[81] https://www.embrapa.br/en/international

[82] maizegdb.org

[83] cals.iastate.edu/news/releases/iowa-state-university-and-university-hawai-i-researchers-receive-collaborative-award

- Professor Buckler of the Institute for Genomic Diversity at Cornell University specializes in studying germplasm diversity and genotype to phenotype correlation for corn.[84]
- The Plant Genomics Group at the Cold Spring Harbor Laboratory has been instrumental in genomic and epigenomic sequencing of different varieties of corn with a specific focus on biofuels.[85]
- Soybase is a genetics and genomics database funded by USDA. It contains a genome sequence browser, information about mutant and other soybean genetic stocks and a gene expression atlas.[86]
- The Chinese Academy of Sciences recently published a pan genome of wild and cultivated varieties of soybeans.[87]
- The Center for Soybean Research at the Chinese University of Hong Kong specializes in studying germplasm diversity of soybeans in East Asia, including the development of traits such as stress tolerance and yield stability.[88]

Micro and drip irrigation

- Kansas State University aims to develop and deploy better irrigation technologies in the state. Toward that end, the university: 1) issues annual evapotranspiration estimates to improve farmers' assessments of irrigation needs; 2) has developed a center pivot irrigation system and irrigation software that are both being deployed at scale; and 3) is developing a subsurface drip irrigation system.[89]

Soil health practices

- The Soil Health Institute is a nonprofit organization that works with stakeholders to identify gaps in research and deployment of soil health measures. It has issued standards and reports on topics from soil measurements and indicators to measuring GHG emissions.[90]
- The Iowa Corn Seed Cover Crop Initiative works to provide seed corn growers with cost-share to help incorporate cover crops into their operation. This project was developed by the Iowa Seed Association in conjunction with the Agribusiness Association of Iowa, Iowa Farm Bureau Federation and Iowa Corn Growers Association. A grant from the Iowa Department of Agriculture under their Clean Water Initiative program provides funding.[91]
- The University of Minnesota's Extension School has issued guidance for planting cover crops in the state.[92]

[84] maizegenetics.net/research

[85] cshl.edu/research/plant-biology/#about

[86] soybase.org

[87] doi.org/10.1016/j.cell.2020.05.023

[88] csr.cuhk.edu.hk

[89] https://www.northwest.k-state.edu/program_areas/irrigation/

[90] soilhealthinstitute.org

[91] sustainableseedcorn.org

[92] Guide to planting cover crops in Minnesota, https://extension.umn.edu/soil-and-water/cover-crops