Iowa's agriculture is losing its Goldilocks climate

Eugene S. Takle, and William J. Gutowski

Citation: Physics Today **73**, 2, 26 (2020); doi: 10.1063/PT.3.4407
View online: https://doi.org/10.1063/PT.3.4407
View Table of Contents: https://physicstoday.scitation.org/toc/pto/73/2
Published by the American Institute of Physics

IOWA'S agriculture IS LOSING ITS Goldilocks CLIMATE

Eugene S. Takle and
William J. Gutowski Jr

Climate conditions for growing corn and soybeans have improved, but current trends indicate they will not last.

CHARLIE NEIBERGALL/AP/SHUTTERSTOCK

Eugene Takle is an emeritus professor in the department of agronomy, and **William Gutowski** is professor of meteorology in the department of geological and atmospheric sciences, both at Iowa State University in Ames.

The Iowa landscape is endowed with rich, deep, dark soils that have high water-holding capacity. Because most of the state's land is flat or gently rolling, agriculture can be practiced with large, efficient machinery. Historically, Iowa's average climate is characterized by a growing season of about five to six months with favorable sunshine and warm temperatures. Its crop-dormant season has low enough temperatures to prevent overwintering of detrimental pests and pathogens. The seasonal cycle of precipitation has a spring–summer maximum and a winter minimum that generally provide a sufficient and timely supply of water to support high crop densities without the need for irrigation.

Iowa's climate, along with its rich soil, has made the state the national leader in producing corn and raising animals that feed on corn—namely, hogs and laying hens. Iowa is also second in the nation in soybean production.

More sophisticated and automated machinery, large amounts of fertilizer and pest-management chemicals, and improvements in crop breeding have made Iowa's agriculture more productive. However, those changes have driven up production costs and reduced diversity to two crops. They have also depopulated vast areas of the state and made profits dependent on a favorable climate for those two products.

Iowa's climate is experiencing increased humidity, early-season rainfall, as well as a reduction in mid- to late-summer maximum daily temperatures. Evidence is mounting that the multidecadal trend of increases in Midwest corn yields, generally attributed to improved technology and management, may also have been partially attributable to the climate becoming more favorable. Midwest agricultural production is important to the national and global food supply and, more recently, to biofuels; its importance motivates us to take a closer look at recent climate trends, future projections of climate for the region, and how the climate will impact agriculture.

One change that has likely contributed to higher yields is humidity high enough to prevent extreme plant desiccation but not so high that it consistently fosters detrimental fungus and mold. Other probable contributions are abundant rains that reliably recharge the deep-soil water reservoir in spring but not so extreme or persistent that they delay or prevent spring tillage and planting; and abundant sunshine with high summer temperatures but not so high as to limit crop growth or reproduction.

Those climate changes have led Iowa to a Goldilocks period with just the right measure and timing of humidity, rainfall, and heat. But it will likely not last. Without major technological advances, by the mid 21st century climate change could decrease Midwest agricultural productivity to 1980s levels.[1]

The physical link between the greenhouse gas heating of our planet and food production in a particular region can be captured by mathematical models; see the box on page 31.

Climate change and Iowa's crops

Iowa's summer daily maximum temperatures over the past 30 years have not followed the upward global trend. Nighttime minimums have increased, but higher humidity, overcast skies, rainfall, and the resulting wet soil have decreased the fraction of solar radiation converted to sensible as opposed to latent heat. More latent heat causes even higher humidity and limits warming, which has led to a so-called warming hole in the central US.[2]

Water stress on crops is measured by the water-vapor deficit—the difference between the saturation vapor pressure of water in a leaf and the ambient water-vapor pressure. Rising dew-point temperatures due to enhanced moisture flow from the Gulf of Mexico, coupled with steady or declining maximum daily temperatures, mean that the

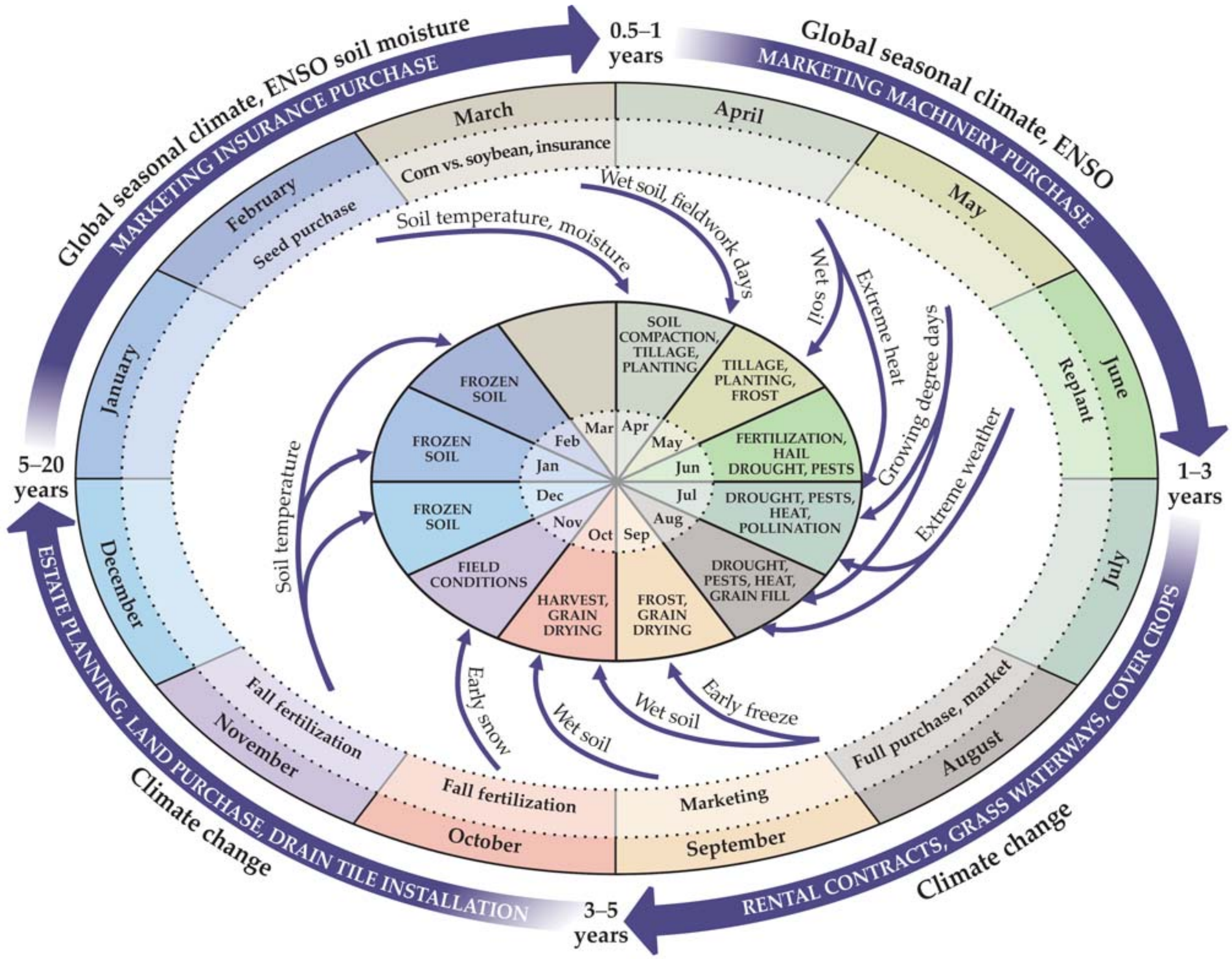


FIGURE 1. A DECISION CALENDAR for Midwest corn producers showing climate forecast lead times. The outer monthly ring shows the timing of typical decisions producers make; the inner monthly ring shows the activities and climate outcomes related to those decisions. The lengths of arrows connecting the rings indicate the time lapses, or climate forecast lead times, between decisions and their impacts; the labels on the arrows show the relevant climate condition. The outer ring of arrows indicates decisions farmers make that are affected by seasonal to decadal climate conditions and changes. For instance, producers in Florida might use a six-month forecast of the El Niño/Southern Oscillation (ENSO) conditions to estimate soil moisture levels over the growing season. Farmers in Iowa might use forecasted decadal trends in growing season precipitation to decide on whether to install subsurface drainage tile. (Adapted from ref. 18.)

daytime vapor-pressure deficit, and hence crop stress, has decreased. Those factors lead to the counterintuitive conclusion that climate change has decreased, not increased, water stress in plants in Iowa. The lack of new irrigation systems in the state suggests that farmers are not having a problem with water stress in crops.

The water supply for the spring recharge of the agricultural soil-moisture reservoir has increased over the past 30 years. But now moisture is more frequently impeding tillage and planting operations and is increasing soil erosion. In 2013 the US Department of Agriculture reported that more than 1100 square miles of corn and soybean cropland in northwest Iowa were not planted because of persistent rains during the planting season.

Rising humidity from Gulf moisture, increased spring rain, and subsequent increases in soil surface evaporation in late spring and summer are leading to longer periods of rain and dew remaining on foliage. Those conditions increase the growth of molds and fungi and contribute to increases in infections and mycotoxin contamination in both preharvest and stored grain.

Greater humidity and cloudy skies trap more IR radiation, which suppresses nighttime cooling of near-surface air. By midsummer corn plants have reached their maximum height; for the remainder of the growing season, they convert atmospheric carbon into seed mass. Cooler nighttime temperatures lengthen that so-called grain-filling period, and warmer ones shorten it. Therefore, higher nighttime temperatures from climate change reduce carbon mass accumulation in grain and tend to lower yields.[3]

The most favorable temperature range for vegetative development of corn is the high 70s to low 90s °F; soybeans grow best in the mid 70s to mid 90s. Pollination and seed formation peak in cooler conditions:[4] Corn favors low 60s to mid 70s, and soybeans do best in mid 60s to mid 80s. At temperatures above 100 °F, vegetative development and reproduction pause in both crops. The reduction of daytime temperatures in Iowa because of generally wetter conditions has improved both plant development and seed formation for corn and soybeans.[5]

Other results of recent global climate change have been favorable for agricultural production in Iowa. The longer growing season allows for planting of longer-season hybrids that capture more carbon and thus have higher yields. More seasonal rainfall and stored water, along with fewer extreme heat events, have prompted farmers to plant more seeds per acre—30 000 or more now compared with less than 20 000 per acre 40 years ago for corn. Those favorable changes, and farmers' adaptations to them, have been credited with a 28% greater yield, approximately 1.2 metric tons per hectare, or 19.3 bushels per acre,[5] since 1981.

Adapting to climate change

Arguably the strongest passion of a Midwest farmer is the vernal urge to get seeds planted once the soil temperature reaches 50 °F. It is no surprise then that farmers have been some of the first to detect a subtle but systematic shift in that long-awaited launch point. Warmer average spring temperatures caused by global warming and a rise in humidity—water vapor is a strong greenhouse gas, so higher humidity increases IR absorption—have enabled farmers to begin planting in Iowa, on average, about 10 days earlier in the past 20 years than they did in the 20th century.[4]

Farmers know that the current climate is not the same as that in the last quarter of the 20th century. Over many generations, they have learned to adapt to challenges: pests, price swings, market volatility, and the costs of machinery and fertilizer. Farmers also adapt to persistent adverse weather conditions by, for example, planting on multiple dates and planting multiple corn varieties that have different pollination periods. That approach spreads out the risk of losing an entire crop from a single heat wave.

Seed providers have improved the drought tolerance of hybrid corn, but tolerance to extreme heat and waterlogged soil remains elusive. More frequent and intense rain events have left narrower windows for crucial spring fieldwork, so farmers are purchasing larger planters that can be pulled across fields faster. A 90-foot-wide corn planter is currently being marketed in Iowa; it can plant an area the size of a football field in less than 46 seconds, at least doubling the planting speed of two decades ago.

Intense spring rains on bare soil would enhance soil erosion were it not for the recent increased use of mitigation techniques. Those include fall-planted cover crops to protect the soil, no-tillage practices that leave more surface detritus, perennial grass cover in shallow gullies, water management to reduce runoff, row crops planted on landscape contours rather than up and down slopes, and narrow perennial-grass prairie strips that suppress surface runoff.

Increased occurrences of water-logged soil such as that shown in the opening image have prompted more installation of subsurface drainage tile—perforated pipe that captures and transports soil water to streams and rivers—at closer spacing and even on sloped surfaces. It is estimated that more than 2 million miles of drainage pipe lies under the Iowa landscape.

Higher humidity has driven increased spraying for pathogens and delays in harvesting soybeans. The legumes do not separate well from wet pods, so some farmers have purchased larger, faster bean-harvest equipment to compensate for shorter dew-free harvest periods.

Precision agricultural equipment and more climate analysis technologies are being implemented in the field. Most Midwest farmers make decisions based on short-term weather information; far fewer use seasonal or long-term climate projections. The site-specific and temporally resolved nature of seasonal to annual weather conditions needed for agricultural decisions demand forecast accuracy beyond current levels. Figure 1 shows the relationship between when producers make weather and climate-related decisions and when the impacts of those decisions are seen.

The long lag time between the events highlights the need for improved climate forecast products that farmers will use to estimate crop-relevant conditions weeks to years or even decades into the future. For example, crop inputs, such as seeds, fertilizer, and pest-control chemicals, are purchased months before they are used. If planting is delayed from mid-April, which is optimum for corn in Iowa, until the end of May or beyond, as in 2013 in Iowa and 2019 in both Iowa and Illinois, the reduced growing season may be too short for the longer-season seed variety that was purchased. So even though adaptations may be available, they can come at a price.

Projected trends and agricultural impacts

The conditions underlying recent increases in Midwest humidity and, consequently, high spring and early summer rainfall

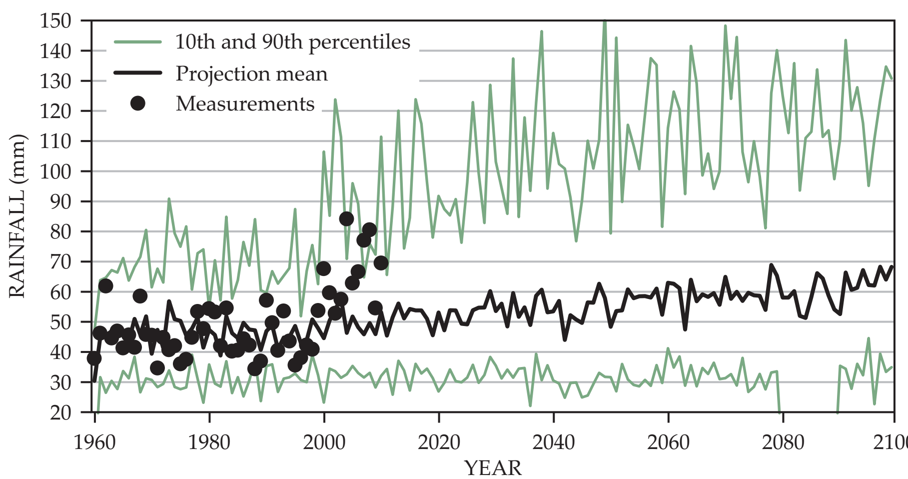


FIGURE 2. BASIN-AVERAGE ANNUAL MAXIMUM DAILY PRECIPITATION (AMP) for the Cedar River Basin at US Highway 30 as represented by the average of 19 global climate simulations for the period 1960–2100 and an ensemble of emission scenarios. The black line is model average AMP, and green lines are the 10% and 90% boundaries of AMP. Black dots are measured values from 1960 through 2009. (Adapted from ref. 8.)

are closely linked to the rise in global mean temperatures.[6] They are therefore likely to persist over the coming decades.[7] A study of average annual maximum daily precipitation (AMP) for a large basin in eastern Iowa comprising 14% of the area of the state revealed that global climate models can capture the increase in AMP between the 20th and early 21st century.[8]

Modeled average AMP values for the Cedar River Basin (figure 2) rise slightly from 1960 through the end of the 21st century. The trend of the 90th percentile line, however, shows that models project a rise in extreme rainfall beginning around 2000 and then a leveling off to a value about 2.5 times the almost-constant 20th century value. The upward trend in the models' extreme high rainfall is borne out by the data and likely to continue for a couple of decades. In that case, the extreme high precipitation over large areas of the state would range from 2.5 to 3.0 times the amounts recorded in the 20th century. The short period of observed data for the 21st century contained no years of low AMP values to validate the once-per-decade low AMP projections.

Heavy spring rains creating waterlogged soil will likely decrease the number of acres planted with corn or soybeans. Rain events exceeding 1.25 inches will also become more frequent and thus worsen soil erosion. The prevalence of bacterial plant diseases and the number and intensity of fungus and disease outbreaks are expected to rise with the higher temperatures and heavier spring rain. Warmer soil and more moisture will lead to more loss of soil carbon and poorer surface-water quality through eroding soil particles and nutrients. Riverine nitrogen levels are particularly exacerbated by alternating years of extreme drought and flood.

According to the US National Climate Assessment, temperatures during five-day summer heat waves are projected to increase more in the Midwest than in any other region of the US.[9] Higher August temperatures reduce the length of the grain-filling period for corn. Higher extremes can also interfere with reproduction.[3] Current average temperatures for a five-day heat wave in Iowa are about 92 °F; by the mid 21st century, that is projected to rise by 5 °F if future greenhouse gas emissions are low and 11 °F if they're high. Even under a medium-emission scenario, projections indicate that, on average, by the mid 21st century one year out of two in Iowa will have at least one summer five-day period when pollination of corn and soybeans will fail.

Increases in growing-season temperature in the Midwest are projected to be the largest factor contributing to declines in the productivity of US agriculture.[1] The suppression of summer daytime maximum temperatures that created the warming hole in the central US is projected to abate, at which point the underlying warming—particularly under higher carbon emission scenarios—will be unmasked and create a "warming hill" and a spatial peak in vapor-pressure deficit, both centered over Iowa[10] (see figure 3).

Biophysical crop-growth models that include future climate scenarios from global models project yields of commodity crops to the middle and end of the 21st century.[10–13] In regions where corn is currently grown, results typically show that yields could drop by 5% to more than 25% below extrapolated trends; that figure is more than 25% for soybeans in the southern half of the region. The models project new areas coming into production outside the northern borders of the corn belt and loss of production on the western edge.

Warming winters with higher soil temperatures are expected to promote the survival and reproduction of insect pests. A northward expansion of new insect pests and crop pathogens into the Midwest already has been observed.

Recent simulations for the high carbon emission scenario suggest that increased droughts between high-rainfall years will be the largest threat to US rainfed corn production in the short term. However, beyond midcentury, high temperature and heat stress will be the dominant constraints. Elevated atmospheric CO_2 can have a fertilizing effect that will partially, but not entirely, offset crop-yield declines caused by climate extremes. That effect is greater for soybeans than for corn.[10]

Adapting for the future

Farmers have used various adaptation strategies over the past four decades. Some were aimed at preventing yield reductions due to adverse weather, and others took advantage of favorable climate changes. Identifying which adaptation strategies to use moving forward will depend on availability and cost.

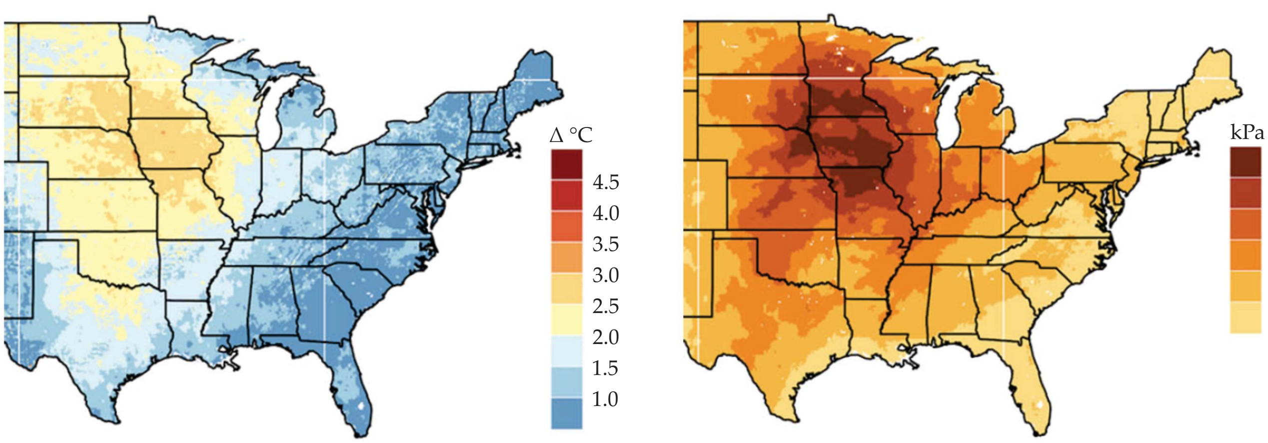
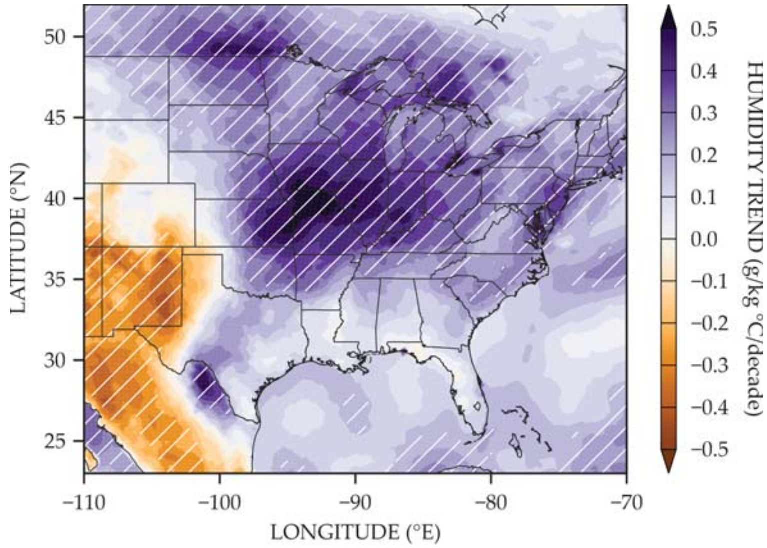


FIGURE 3. PROJECTED CHANGES IN MAXIMUM GROWING-SEASON TEMPERATURES (left) and maximum water-vapor-pressure deficit (right) by the end of the 21st century. The changes are downscaled by use of the Weather Research and Forecasting climate model for the medium-carbon-emissions, or RCP 4.5, scenario. (Adapted from ref. 10.)

THE PHYSICAL BASIS FOR CLIMATE CHANGE IN IOWA



Surprises can emerge from a mathematical description of moist gas circling a rotating planet. The physical system's dynamics and thermodynamics are governed by a set of nonlinear second-order partial differential equations. In Iowa, the most notable climate changes have been higher humidity, more frequent and intense rain events, and a reduction in the daily range of temperatures. Those changes are linked, since higher humidity—especially in spring and early summer—creates more intense rain events and cloudiness that, in turn, reduce daily maximum temperatures and increase daily minimums.

Most of Iowa's warm-season rainfall can be traced to moisture flowing from the Gulf of Mexico. In spring and summer, northward moisture transport is produced by a west-to-east pressure gradient created by a strengthened high-pressure region over Bermuda and a low-pressure region over the Rocky Mountains.[6] The local force of that pressure gradient, in balance with the local Coriolis force of Earth's rotation, creates a northward flow known as the Great Plains low-level jet (GPLLJ) about 1.5 kilometers above the surface.

Mesoscale convective systems (MCSs) are long-lived, heavy-rain-producing weather systems that generate 30–70% of the warm season precipitation in the central US.[6] The GPLLJ provides MCSs with a nocturnal supply of latent heat and moisture that allows convection—and therefore thunderstorms—to persist through the night without solar radiative forcing. That makes the central US unique; it's the only region of the country to have a nocturnal maximum in daily precipitation in the spring and summer.

Zhe Feng and coworkers at Pacific Northwest National Laboratory, using data from about 1.5 kilometers above Earth's surface,[6] traced the increase in Iowa's April-May-June (AMJ) rainfall during MCS occurrences over the period of 1979–2014. The map shows trends in specific humidity—the mass of water vapor per unit of dry air mass—over that period; hatched areas indicate greater than 95% confidence. The researchers attribute the changes to a warmer Gulf of Mexico, which has created a dome of higher-moisture air over the north central Gulf and adjacent southern states. That dome fuels the GPLLJ and, in turn, MCSs, which convert the moisture into more frequent and intense precipitation across the Midwest.

Surface observations in Iowa and across the Midwest corroborate a rise in the AMJ atmospheric water vapor, or absolute humidity, a measure that does not require a concurrent atmospheric pressure measurement. According to the Clausius–Clapeyron relationship, global atmospheric water vapor increases by about 6–7% per degree Celsius of warming. Between 1985 and 2014, the global mean temperature has risen by about 0.56 °C, so global background absolute humidity has risen by 3.6%, or 1.2% per decade. By contrast, surface measurements reveal a rise in absolute humidity in Iowa of about 4.4% per decade. As an outcome of that increase, Iowa AMJ precipitation over the 20th century averaged 11.6 inches but has increased by 2.2 inches, or 19%, over the past three decades, with the attendant impacts discussed in this article.

The GPLLJ and MCSs have long been recognized as central elements of Iowa's AMJ climate that until recently have provided just the right amount of rain at just the right time to be beneficial for Iowa's agriculture. However, enhanced Gulf temperatures and a strengthened GPLLJ that we have traced to global climate change from increased global atmospheric greenhouse gas concentration[2,7] have created significant problems for Iowa's agriculture that are likely to increase in the future.

Climate adaptations may increase production, but an important question for farmers is, Will they increase productivity? Xin-Zhong Liang and coworkers at the University of Maryland used total factor productivity—the ratio of outputs to inputs—as a measure of productivity rather than production.[11] Under the medium-carbon-emissions future climate scenario, they conclude that all the productivity gained by US agriculture from 1981 to 2010 will be reversed by 2035.

Other research concludes that known and practiced adaptations will have marginal benefits under moderate climate change for some crop systems, but their effectiveness will be limited under more extreme conditions of medium- or high-emission scenarios.[14] Developing a more resilient agricultural landscape and agrarian society of land managers and agribusiness providers to cope with climate change will require socioeconomic, cultural, and institutional restructuring, which must be guided by informed policies and implemented at scales beyond the farm.[15]

Agriculture can be more than just crop production; it can also be a carbon-management tool for climate change mitigation. Land use change by humans—in particular, the repeated tillage of agricultural soil—has resulted in substantial loss of carbon from soils. But by returning that carbon, the soil could also serve as a land reservoir for carbon capture and storage.

Roughly half of the carbon in Iowa soils has been lost through tillage of the native tall-grass prairies, so theoretically, that carbon could be returned if economically viable sequestration methods were developed. Such practices would be beneficial for grain production because the recarbonized soil would have a better texture for reducing compaction and holding water and nutrients. Alternative land management practices, such as use of prairie strips in row-crop fields, can also contribute to carbon sequestration. Deep-rooting prairie plants provide ecological and environmental benefits without an overall production penalty.

Healthy soil effectively holds water and nutrients needed to maintain a rich and diverse microbial population that, in turn, sustains plant life. One way to rebuild agricultural soil quality is with organic carbon material that resists decomposition, such as biochar. Such treatment would not only bring back the nutrient- and water-holding capacity of higher soil carbon,[16] but also place agriculture in a leading role in mitigating climate change. Long-term studies show that a one-time biochar application of 10 tons per acre can increase crop yield by 13 bushels per acre. The response is highly variable depending on the soil and year, and the effect is larger on degraded and otherwise poor-quality soils.

Positive outcomes from the use of biochar prompted the "4 per 1000" initiative at the 2015 Conference of Parties meeting in Paris; the conference is held annually under the United Nations Framework Convention on Climate Change. The initiative calls for increasing stored organic carbon in soils by 0.4% per year. If achieved, that would store carbon at a rate of about 6 gigatons per year, a significant fraction of the roughly 10 gigatons per year emissions rate in recent years. However, that's an ambitious goal; closer to 1 gigaton per year might be more realistic.

The physics of coping with climate change

Iowa's climate underscores the danger in jumping to conclusions about the impact of climate change on a particular location. Earth's climate system is a huge thermodynamic engine that takes in solar energy and transforms it into sensible heat, latent heat, and, through photosynthesis, chemical energy that leads to the formation of plant carbon. Sensible and latent heat help establish pressure gradients that team up with Coriolis forces to distribute heat around the spinning planet. Energy is expelled as IR energy back to space in amounts comparable to incoming solar radiation.

Spatially inhomogeneous heating caused by the different radiation absorptivities of land, water, vegetation, and ice creates a complex climate that defies simplistic predictions of how future seasons will play out at any fixed point. Iowa's crop-favorable moisture conditions are the end product of a sequence of time-sensitive dynamic and thermodynamic processes that link Iowa to the Gulf of Mexico and to global rises in atmosphere and ocean temperatures.

Recently, the cascading effects of atmospheric moisture transport to Iowa have led to moisture levels that are neither too high nor too low and that occur at the right time of year. But Iowa's agriculture has a fragile Goldilocks relationship to global climate change. A continued increase in moisture transport will lead to an excess of the humidity, precipitation, and flooding that has begun to affect the state in the past 30 years. A decrease in moisture transport, which is projected to occur in the latter half of the 21st century, will reduce critical spring and summer rainfall and lead to markedly higher daily summer maximum temperatures that exceed the vegetative and reproductive limits of Iowa's current crops.

Science-based policies and agronomic research are needed to maintain grain production for food and feed supplies in the current half of the 21st century.[4,14] The research would provide information about managing carbon-cycle dynamics through soil amendments, tillage, and the use of perennials; controlling water through drainage, storage, and irrigation; and understanding the root structures, water- and nitrogen-use efficiencies, and declining nutritional values of plants. Beyond midcentury, increases in growing-season heat[10] are projected to lead to substantial crop-yield reductions.[13] That level of disruption calls for transformative developments in agriculture[13] and broader societal recognition of the threats of climate change.[17]

We dedicate this paper to the memory of our friend and colleague, Ray Arritt, from whom we learned so much about the Great Plains low-level jet and convective precipitation in the central US.

Partial financial support was provided for Takle from NSF grant 1701278 and USDA/NIFA/Hatch fund IOW04414 and for Gutowski by NSF grant AGS-1243030 and US Department of Energy grant DE-SC0016438. Personal communications with Kendall Lamkey, Sotirios Archonoulis, and Andy VanLoocke strengthened the manuscript.

REFERENCES

1. US Global Change Research Program, *Fourth National Climate Assessment, Volume II: Impacts, Risks, and Adaptation in the United States* (2018).
2. Z. Pan et al., *Geophys. Res. Lett.* **31**, L17109 (2004).
3. J. L. Hatfield et al., *Agron. J.* **103**, 351 (2011).
4. C. L. Walthall et al., *Climate Change and Agriculture in the United States: Effects and Adaptation*, US Department of Agriculture Technical Bulletin 1935 (2012).
5. E. Butler, N. Mueller, P. Huybers, *Proc. Natl. Acad. Sci. USA* **115**, 11935 (2018).
6. Z. Feng et al., *Nat. Commun.* **7**, 13429 (2016).
7. K. H. Cook et al., *J. Clim.* **21**, 6321 (2008).
8. C. J. Anderson, D. Claman, R. Mantilla, *Iowa's Bridge and Highway Climate Change and Extreme Weather Vulnerability Assessment Pilot*, Final Report, Iowa State University (March 2015).
9. US Global Change Research Program, *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (2017).
10. Z. Jin et al., *Glob. Change Biol.* **23**, 2687 (2017).
11. X.-Z. Liang et al., *Proc. Natl. Acad. Sci. USA* **114**, E2285 (2017).
12. E. S. Takle et al., *Economics* **7**, 2013-34 (2013).
13. B. Schauberger et al., *Nat. Commun.* **8**, 13931 (2017).
14. J. L. Hatfield, L. Wright-Morton, B. Hall, *Clim. Change* **146**, 263 (2018).
15. S. M. Howden et al., *Proc. Natl. Acad. Sci. USA* **104**, 19691 (2007).
16. Y. Ding et al., *Pedosphere* **27**, 645 (2017).
17. A. K. Wilke, L. Wright Morton, *Sci. Commun.* **37**, 371 (2015).
18. E. S. Takle et al., *Earth Interact.* **18(5)**, 1 (2014).

PT