

Are we approaching a water ceiling to maize yields in the United States?

EVAN H. DELUCIA,^{1,2,3,4,5,6,†} SHILIU CHEN,^{5,8} KAIYU GUAN,^{2,4,5,6,8} BIN PENG,^{5,6} YAN LI,⁵
 NURIA GOMEZ-CASANOVAS,^{1,2,3} ILSA B. KANTOLA,^{2,3} CARL J. BERNACCHI,^{1,3,4,9} YUEFEI HUANG,^{7,8}
 STEPHEN P. LONG,^{1,2,3,4,6,10} AND DONALD R. ORT^{1,3,4,10}

¹Department of Plant Biology, University of Illinois, Urbana, Illinois 61801 USA

²Institute for Sustainability, Energy, and Environment, University of Illinois, Urbana, Illinois 61801 USA

³Carl R. Woese Institute for Genomic Biology, University of Illinois, Urbana, Illinois 61801 USA

⁴Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois, Urbana, Illinois 61801 USA

⁵Department of Natural Resources and Environmental Science, University of Illinois, Urbana, Illinois 61801 USA

⁶National Center for Supercomputing Applications, University of Illinois, Urbana, Illinois 61801 USA

⁷Department of Hydraulic Engineering, State Key Laboratory of Hydrosience and Engineering, Tsinghua University, Beijing 100084 China

⁸State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, Xining, Qinghai 810016 China

⁹USDA-ARS Global Change and Photosynthesis Research Unit, Urbana, Illinois 61801 USA

¹⁰Department of Crop Science, University of Illinois, Urbana, Illinois 61801 USA

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Abstract. While annual precipitation in much of the US Corn Belt is likely to remain constant, atmospheric vapor pressure deficit (VPD), the driver of crop water loss (evapotranspiration; ET), is projected to increase from ~2.2 kPa today to ~2.7 kPa by mid-century primarily due to the temperature increase. Without irrigation, it has been hypothesized that the increase in VPD will create a ceiling to future increases in maize yields. We calculated current and future growing season ET based on biomass, water use efficiency, and the amount of yield these levels of ET would support for maize production in the Midwest USA. We assumed that the production of more grain will necessitate a proportional increase in the production of biomass, with a corresponding increase in ET. Here we show that as VPD increases, maintaining current maize yields (2013–2016) will require a large expansion of irrigation, greater than threefold, in areas currently supported by rain. The average predicted yield for the region of 244 ± 4 bushels/acre ($15,316 \pm 251$ kg/ha) projected for 2050, assuming yield increases observed for the past 60 yr continue, would not be possible with projected increases in VPD, creating a water ceiling to maize yields. Substantial increases in maize yields and the production of high yielding grasses for bioenergy will require developing cultivars with greater water use efficiency, a trait that has not been a priority for breeders in the past.

Key words: atmospheric vapor pressure deficit; climate change; crop yield; irrigation; water use efficiency.

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† **E-mail:** delucia@illinois.edu

INTRODUCTION

Producing enough food and plant-based bioenergy for the increasingly affluent population is a challenge made even more daunting by climate change. Global demand for food and fiber may increase by more than 100% from 2005 to 2050 (Tilman et al. 2011). While the rate of increase in crop yields in much of the world has been more modest than observed for the USA (Ray et al. 2013), the introduction of hybrids and improved genetics and agronomic practices has driven a >3-fold increase in maize yields over the past 60 yr in the USA, from ~53 bushels per acre (3328 kg/ha) in the 1956 to ~170 bushels per acre (10,676 kg/ha) in 2016 (USDA NASS 2017; Appendix S1). Were this linear increase to continue, maize yields would exceed 230 bushels per acre by 2050 (Appendix S1). Indeed, contemporary record maize yields in the United States are more than twice this value (Agfax 2016, <https://agfax.com/2016/12/20/georgia-farmer-at-top-of-500-bushel-national-corn-yield-contest-dtn/>), and predictions based on the theoretical limits to net primary production would be higher still (DeLucia et al. 2014). A number of changes in the climate system will, however, conspire to work against extrapolating these historic increases in grain yields into the future (Lobell and Field 2007, Zipper et al. 2016, Liang et al. 2017, Angel et al. 2018).

The current rate of accumulation of greenhouse gases in the atmosphere portends an average temperature increase, relative to the period from 1961 to 1990, for the Midwest USA of $2.7^{\circ} \pm 1.0^{\circ}\text{C}$ (range) by mid-21st century, with little or no change in average annual precipitation (Pryor and Barthelmie 2013, Pryor et al. 2013). Small changes in average precipitation belie important changes in its timing, however. Intense spring storms combined with longer droughts later in the growing season can decrease yields. Perhaps more importantly, a warmer atmosphere will drive greater evaporative demand and thus greater water consumption to produce the same yields.

In maize, the proportion of aboveground biomass allocated to grain, the harvest index (HI), has remained stubbornly constant over time (Hay 1995, Vega et al. 2000). The HI for USA maize increased only from ~0.45 in 1930 to ~0.50

in the latter half of the 1970s (Hay 1995), with values only slightly higher (0.54) for two high yielding varieties (Hao et al. 2016). If this small change over a long period of time indicates that HI has reached its biological limit, future increases in maize yields will require greater production of aboveground biomass, and greater aboveground biomass will necessitate greater water consumption. Currently, total annual evapotranspiration from maize in the central part of the rain-fed Corn Belt is ~70% of average annual precipitation (Zeri et al. 2013).

The force driving water loss from vegetation and soil is atmospheric vapor pressure deficit (VPD), calculated as the difference between the water vapor air can hold at saturation and actual water vapor pressure. Over the past 35 yr, increasing temperature has driven an increase in average annual VPD for the continental USA (Ficklin and Novick 2017). Ensemble climate models indicate this trend will continue into the future as temperatures increase further (Ficklin and Novick 2017), with average July values for the Midwest projected to increase from ~2.2 kPa today to ~2.7 kPa by mid-century (Lobell et al. 2014). The difference between the water vapor pressure in the leaf, which is near saturation, and the water vapor pressure of the surrounding dry air drives water loss from plants. All else being equal, projected increases in VPD will cause a corresponding increase in evapotranspiration (ET) even to support current yields, and the increase in ET will be magnified as breeders and farmers seek even higher yields.

Previously, it was suggested that by increasing water demand relative to its availability, rising VPD could limit further increases in maize yields (Ort and Long 2014). Climate models suggest minor changes in growing season rainfall in the U.S. Midwest, and thus, VPD and temperature changes may be the primary driver for the changes in crop growth and yields (Angel et al. 2018). Here, we conducted a theoretical analysis to address three questions: (1) Can current levels of rainfall support today's yields as VPD increases? (2) What are the maximum achievable maize yields in the rain-fed Midwest US with projected increases in VPD? (3) To what extent will achieving these yields require an expansion of irrigation? This region is dominated by maize and soybean largely grown in rotation, and 88%

of the area under these crops in the United States currently does not receive irrigation (USDA NASS 2016). We focus on maize because it has greater sensitivity to VPD than soybean (Lobell et al. 2014), making it more likely to achieve VPD-dependent water limitations. Our analysis provides an upper boundary to maize yields without irrigation as our estimates do not include the direct effect of increasing temperature and VPD on crop productivity (Lobell and Field 2007, Lobell et al. 2014). Using spatially resolved data to calculate aboveground biomass and ET from current yield data (USDA NASS 2017), we then estimate maximum yields under projected mid-century values for VPD (Appendix S1).

MATERIALS AND METHODS

A step-by-step description of the calculations of the highest attainable yield under current rain-fed and irrigated conditions, as well as the amount of irrigation needed to support projected future maize yields, is provided in the Supplemental Information; an overview is presented here. Note, in this analysis data sets with different spatial resolutions were used by aggregating them to the county level.

We relied on a parsimonious and well-validated hydrological model (Laio et al. 2001, Rodriguez-Iturbe et al. 2001, Rodriguez-Iturbe and Porporato 2005; Appendix S1) to calculate the highest attainable yield and projected amount of irrigation. In this model, soil moisture was calculated as the difference between precipitation, ET, leakage, and runoff at a daily time step. Each county was treated as a single soil column in the model. In contrast to traditional hydrological models where ET is usually a diagnostic output, ET in our model was a critical input and was derived from maize yields and water use efficiency (WUE; Appendix S1). The highest attainable yields under rain-fed conditions (e.g., without irrigation) under contemporary and future VPD were calculated by increasing maize yields incrementally in each county until the corresponding ET caused soil moisture to drop below the permanent wilting point for 3 out of any 5 consecutive days (Appendix S1). Irrigation was deemed necessary whenever calculated soil moisture was below the

permanent wilting point of maize, and was applied until local soil moisture reached field capacity.

The calculation of growing season ET was based on net primary production derived from maize yields and WUE (defined as the total dry mass of maize divided by growing season ET; DeLucia et al. 2014), scaled by VPD and other factors (Appendix S1). Total accumulated NPP for maize for a given year was calculated from reported yield (USDA NASS 2017) or projected yield, assuming fixed allocation to roots and grain (Prince et al. 2001) and a constant HI of 0.50 (Hay 1995, Hao et al. 2016). Growing season ET was further disaggregated to the daily step for the hydrological modeling for irrigation, and the temporal disaggregation was conducted to convert the total accumulated NPP and integrated WUE during the growing season into daily values for calculating daily ET (Appendix S1). In the above calculation, we used the seasonal cycle (but not the absolute value) of MODIS (Moderate Resolution Imaging Spectroradiometer) NPP product (MOD17A2H.V006, Running et al. 2004) to disaggregate the yield-based NPP estimation, and likewise, we used the seasonal cycle of ALEXI (Atmosphere-Land Exchange Inverse) ET (Anderson et al. 2011), a satellite-driven, state-of-the-art ET product, to disaggregate growing season ET to daily ET and daily WUE. The effect of CO₂ on WUE (Hussain et al. 2013) was also considered under future climate condition. We calculated current (2013–2016) biomass produced and ET during the growing season for each county in the area of the U.S. Midwest that produces 75% of nation's maize.

Maize yields have experienced a linear increase over the past 60 yr (USDA NASS 2017; Appendix S1), a trend that is expected to continue with increasing demand for food and bioenergy. Here we extrapolated the yield increases over the past 60 yr (Appendix S1) forward to 2050 to estimate the projected future maize yields (+40 ± 2%, 95% Prediction Interval). We then calculated corresponding biomass and ET based on the maize yields as described above, where future VPD was calculated following the approach of Lobell et al. (2014) from projected maximum air temperature and specific humidity under representative concentration pathway (RCP) 8.5 from the average of 20 climate models (Taylor et al. 2012).

This theoretical analysis and its corresponding results are subject to a number of uncertainties, chief among them are the uncertainties embodied in future climate projections and the assumptions that we used. Because our analysis assumes a constant harvest index of 0.5, and modern maize varieties vary somewhat around this value, we examined how variation in this value affected projections of the highest attainable maize yields. Similarly, to assess the sensitivity of irrigation calculation, we tested different thresholds of soil moisture to initiate irrigation. We found that changes in both variables had modest effects on the projected yields and irrigated land area (Appendix S1). The projected maximum yields under future VPD, as well as the projected amount and area of irrigation, reported here are based on the median values from 20 different general circulation models (GCMs), and variation in results when driving the calculations with individual GCMs is reported in Appendix S1: Figs. S7, S8. Validation of the hydrologic model is provided in Appendix S1. To calculate yields in kg/ha, units in bushels/acre were multiplied by 62.77, assuming a constant density of 56 lb/bu (Iowa State University 2018).

RESULTS AND DISCUSSION

Our theoretical analysis indicates that the increase in atmospheric VPD driven by the projected increase in temperature would set a ceiling to future maize yields in U.S. Midwest, and unless intrinsic WUE of maize is improved, exceeding this ceiling will require vast increases in irrigation. Currently, average maize yield across the rain-fed region of the US Midwest from our model is ~174 bushels/acre ($10,922 \pm 1255$ kg/ha) with a gradient of increasing yield from west to east, corresponding to a gradient in annual average precipitation (Fig. 1A). This average yield value from our model was similar to the average yield from the USDA NASS data base of 168 bu/acre (Appendix S1). If the improvements in maize yield evident over the last 60 yr were extrapolated to 2050, the average yield for the region would increase to 236 bushels/acre (14,821 kg/ha), with some areas reaching or exceeding 250 bushels/acre (15,700 kg/ha; Fig. 1B). Because HI likely will remain constant, these increases in yield will necessitate the production

of greater biomass with a corresponding increase in ET. With no other environmental changes, and no physiological responses of the crop other than enhanced ET, greater VPD projected in the future would support an average yield of only 209 bushels/acre (13,125 kg/ha) for the rain-fed region, more than 11% below the projected yield gain (Fig. 1C). For most of the rain-fed Midwest, high future VPD reduced potential maximum maize yields projected for 2050 by as much as 25 bushels/acre (1570 kg/ha; Fig. 2). However, some areas in the far east of the region would approach maximum projected yields under future conditions, because of low yields under present conditions.

For only the rain-fed area of the Midwest, maize yields increased with precipitation at low precipitation levels and then became limited by other factors, primarily the water holding capacity of the soil (not shown), at higher precipitation (Fig. 3). The VPD limit to yield was pronounced at low rates of precipitation, where ET would rapidly exceed available water, and similarly at high rates of precipitation where water holding capacity was low and a high proportion of the water runs off.

The water ceiling predicted for maize yields in most of the rain-fed Midwest would be raised somewhat by enhanced WUE caused by CO₂-induced stomatal closure (Fig. 1D). While carbon assimilation of plants with C4 photosynthesis does not respond directly to above-ambient increases in atmospheric CO₂ (Leakey et al. 2006), C4 plants do respond by partially closing their stomata (Ainsworth and Long 2005), decreasing transpiration and increasing WUE. For maize, the 20% reduction in stomatal conductance observed when plants are grown at the CO₂ concentration predicted for 2050 causes a 10% reduction in ET and a 11.1% increase in WUE (Hussain et al. 2013). Incorporating the CO₂-enhanced WUE in our calculation would increase average maximum attainable yields averaged for the Midwest from 209 bushels/acre (13,125 kg/ha) to 231 bushels/acre (14,507 kg/ha; Figs. 1D, 3).

Assuming that maize in the future retains current WUE and HI, this analysis indicates that the increased evaporative demand projected for 2050 will limit maximum yield below that predicted by extrapolating past yield increases forward.

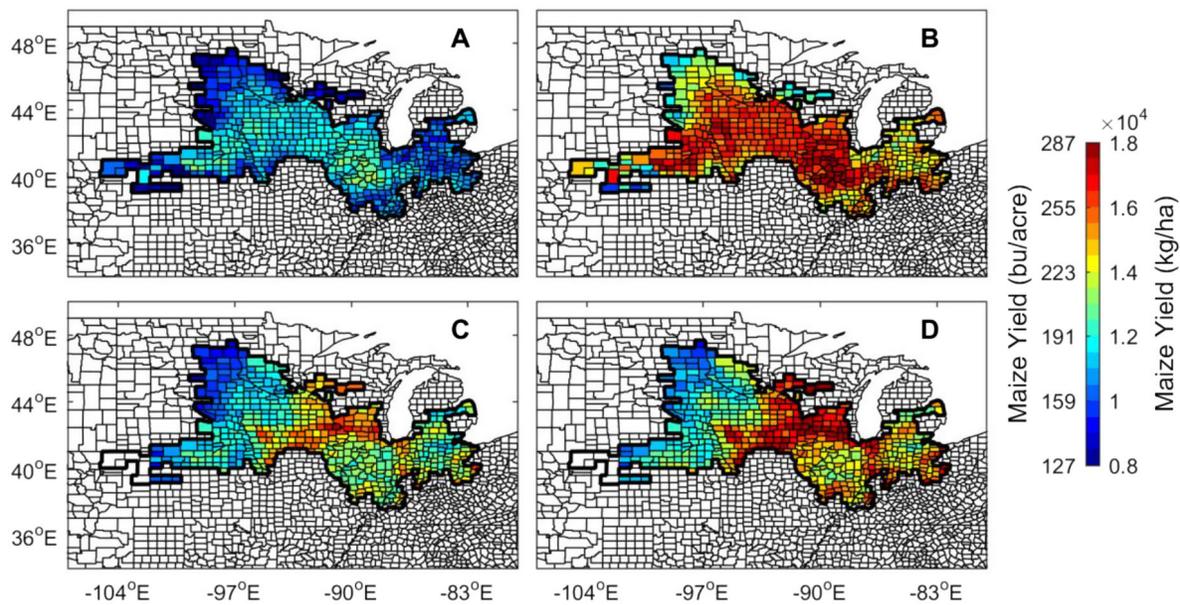


Fig. 1. (A) Current (2013–2016) maize yields by county from USDA NASS (average yield for the core area: 174 ± 20 bushels/acre; $10,922 \pm 1255$ kg/ha); (B) projected maize yields for the core area with current precipitation and VPD assuming that the proportional increase in yield observed over the past 60 yr would continue to 2050 ($+40 \pm 4\%$ Prediction Interval; average predicted yield: 244 ± 4 bushels/acre; $15,315 \pm 251$ kg/ha); (C) projected maximum maize yields for the core area in 2050 assuming current precipitation but an increase in atmospheric VPD (C; average projected yield: 207 ± 14 bushels/acre; $12,993 \pm 879$ kg/ha); (D) projected maximum maize yields for the core area in 2050 with current precipitation but an increase in atmospheric VPD, and a 11.1% increase in WUE from reduced stomatal conductance (average projected yield: 226 ± 17 bushels/acre; $14,186 \pm 1067$ kg/ha). VPD was spatially variable over the region; for current simulations, VPD was 1.35–2.10 kPa, and VPD for 2050 was 1.75–2.61 kPa (daytime values, June–September). The core illustrated in this figure is the area that currently produces 75% of U.S. maize (defined as counties with maize harvested area larger than 50,000 acres, based on 2013–2015 USDA NASS statistics).

However, current yields rarely reach maximum yields, as heat and drought stress, as well as nutrient limitations and other stresses, contribute to a yield gap (Lobell et al. 2009, Muller et al. 2012). In much of the rain-fed Midwest, yields typically are 20–30% below maximum (Lobell et al. 2009). Indeed, this analysis may overestimate the potential to increase maximum yields in the future, as it does not consider the direct effect of heat or drought on maize physiology (Challinor et al. 2014), which will further lower maximum yields and potentially widen the yield gap—a gap that may be widened even further by an increasing frequency of extreme weather events (Lesk et al. 2016, Angel et al. 2018).

Without the discovery of ways to substantially increase HI or WUE, maintaining current maize

yields or dramatically increasing them under greater atmospheric VPD will require an expansion of land under irrigation, as well as increases in the amount of water applied. Our model, run with average environmental conditions for 2013–2016 and contemporary maize yields, predicted that 109,000 km² currently are under irrigation (Fig. 4A), consistent with the irrigated area reported by the US Department of Agriculture (USDA NASS 2012: Appendix S4). If maize yields remain constant, increasing the atmospheric VPD to values projected by 2050 would increase the area under irrigations by more than threefold, to 509,000 km² (Fig. 4B), and to achieve a 40% increase in yield with projected increases in VPD would require an ~6-fold increase in land under irrigation to 772,000 km²

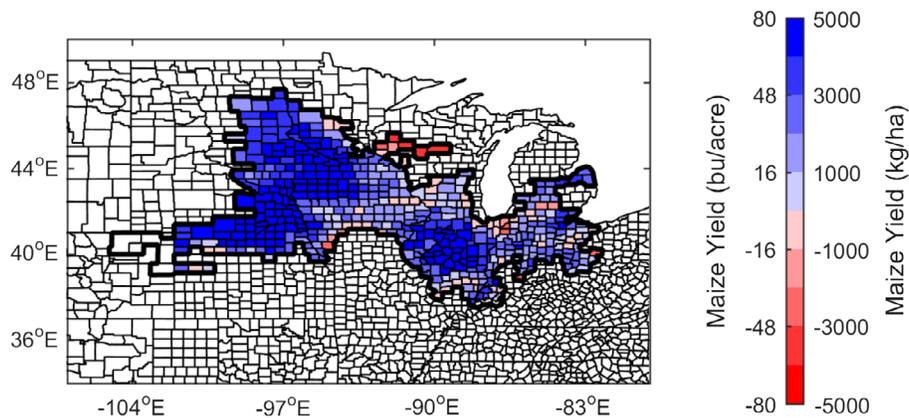


Fig. 2. The difference between the projected maize yields by 2050 assuming that the increase in yield observed over the past 60 yr continues to 2050 ($+40 \pm 4\%$; Figure 1B), and the maximum projected yield under current precipitation but with the future projected atmospheric VPD in 2050 (Figure 1C). The average difference over this core area is 38 ± 14 bushels/acre (2385 ± 879 kg/ha). The area indicated on the map currently produces 75% of U.S. maize. The difference in current and projected future yields varied with differences in VPD projected by different climate models (Appendix S1: Figs. S5, S6).

(Fig. 4C). The future irrigated land area would decrease slightly from 772,000 to 746,000 km² if it is assumed that the increase in atmospheric CO₂ will cause the experimentally measured reduction in stomatal conductance with a corresponding increase in WUE (Fig. 4D). In addition to the increase in land area under irrigation, the amount of irrigation water applied to the core area of the entire Corn Belt would increase from 7.8×10^{10} m³ under current conditions to 10.2×10^{10} m³ in a future with higher yields, VPD, and WUE.

Using a statistical model relating historical area under irrigation to soil moisture deficit, and projecting this relationship forward based on climate projections from global circulation models, McDonald and Girvetz (2013) also predict that the area under irrigation will increase in the future. This increase is predicted to be greatest in regions of the USA currently with a small fraction of arable land under irrigation.

Land under irrigation has expanded globally, and the availability of large volumes of irrigation water ultimately will constrain future crop yields (Siebert et al. 2015). Currently, irrigated maize production in the Midwest, primarily through center pivot irrigation, is mostly located in central and western Nebraska and neighboring Kansas, where annual precipitation is fairly low

(Fig. 4A). Irrigation in this region is primarily from groundwater extracted from the Ogallala Aquifer, a geologic feature that underlies the Great Plains extending south into Texas. Substantial pumping from the Ogallala for irrigation has caused water table declines of as much as 50 m in some areas (Konikow 2013). However, changes in the water table depth are spatially variable, and because of high recharge rates, the declines in northwestern portions of the Corn Belt have been relatively small (Scanlon et al. 2012). Future increases in water extraction for irrigation exceeding rates of recharge may tip the balance leading to declining water table depths in this region.

To meet the water demands of increasing maize yields, irrigation will need to extend eastward across Iowa and Illinois (Fig. 4), areas currently served by rain alone. Iowa and northern Illinois sit over the Midwestern Cambrian-Ordovician Aquifer System, which also extends into parts of Minnesota, Wisconsin, Michigan, and Missouri (Konikow 2013). This aquifer has not traditionally been tapped for irrigation but is widely used by the region's metropolitan areas for municipal and industrial water, leading to substantial depletion. Lake Michigan and the extensive river systems in this region also are potential sources of irrigation water. Increasing

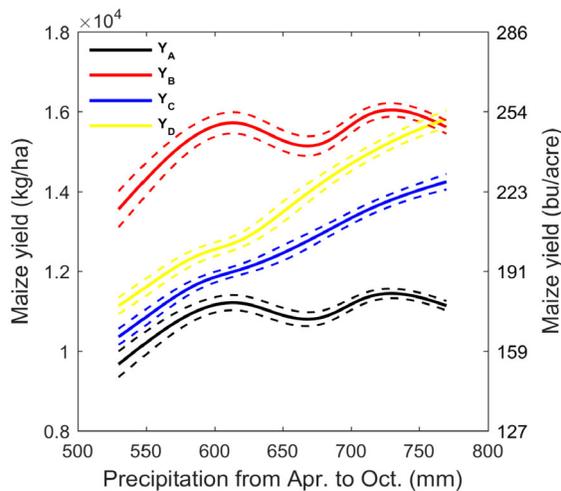


Fig. 3. Average maize yield under current environmental conditions in the rain-fed region of the US Midwest as a function of average precipitation (Y_A , black line, corresponding to Fig. 1A); projected future maize yields by 2050 assuming that the increase in yield observed over the past 60 yr continues to 2050 ($+40 \pm 4\%$), but with current precipitation and atmospheric VPD (Y_B , red line, corresponding to Fig. 1B); projected maximum maize yield by 2050 with current precipitation but higher atmospheric VPD (Y_C , blue line, corresponding to Fig. 1C); projected maximum maize yields in 2050 with current precipitation but an increase in atmospheric VPD, and a 11.1% increase in WUE from reduced stomatal conductance (Y_D , purple line, corresponding to Fig. 1D). Solid lines represent a moving average, and the dashed lines represent 95% confidence intervals.

demand for irrigation water from the Midwestern Cambrian-Ordovician Aquifer System and the Ogallala aquifer will intensify the competition for this resource between agriculture and municipal needs, putting greater pressure on surface water to meet municipal water demands. The projected expansion of irrigation into southern Illinois and parts of Indiana may be even more problematic, as these areas do not overlay a major aquifer system, and irrigation will need to be provided by surface water, potentially reducing stream flow.

Our calculation of the water ceiling to maize yields (Fig. 2) assumes that HI and WUE remain constant at today's levels for crops grown in the future. Improving either of these values would

greatly increase yield under future water availability and atmospheric evaporative demand. Despite selection by breeders, there has been very little improvement in HI (Duvick 2005), suggesting that it may be near its physiological limit. Furthermore, substantial increases in HI may increase the risk of lodging. There may be, however, room to improve WUE.

The extraordinarily low variation in VPD-corrected WUE among C4 crops (Appendix S1: Table S1) led to the speculation that WUE is conserved among maize varieties with different release dates. While few data refute this speculation, there is circumstantial evidence that this may not be the case. Yield for maize hybrids released from 1963 to 2009 increased, but without extracting more soil water (Reyes et al. 2015), leading to the inference that either WUE or HI increased with year of commercialization. Similarly, modern maize hybrids have higher WUE than their parental lines (Chairi et al. 2015), indicating that there may be potential to improve WUE. Considerable variation in instantaneous WUE—the ratio of net photosynthesis to stomatal conductance—in other C4 crops, including sugarcane, switchgrass, and sorghum, suggests that improvement in maize WUE may be attainable (Leakey et al. 2019). While more crop per drop is a laudable goal, increased WUE has not been a target for breeding and has the potential to inadvertently compromise drought tolerance (Blum 2009, Roche 2015).

Opportunities to improve WUE can be found at several spatial and temporal scales. At the level of biochemistry and individual leaves, increasing the rate of photosynthesis by improving chloroplast metabolism or reducing barriers to the transport of CO_2 within leaves (Flexas et al. 2008) will increase WUE. For example, improving the ability of tobacco to respond to excess light increased photosynthesis without a corresponding increase in transpiration (Kromdijk et al. 2016), as would other increases in the biochemical efficiency in the component processes of photosynthesis (Long et al. 2015). Similarly, reducing impediments to the diffusion of CO_2 once it is in the air spaces inside leaves on route to its ultimate site of fixation in the chloroplast, quantified and mesophyll conductance, can increase WUE by increasing carbon fixation without increasing transpiration (Kolbe and

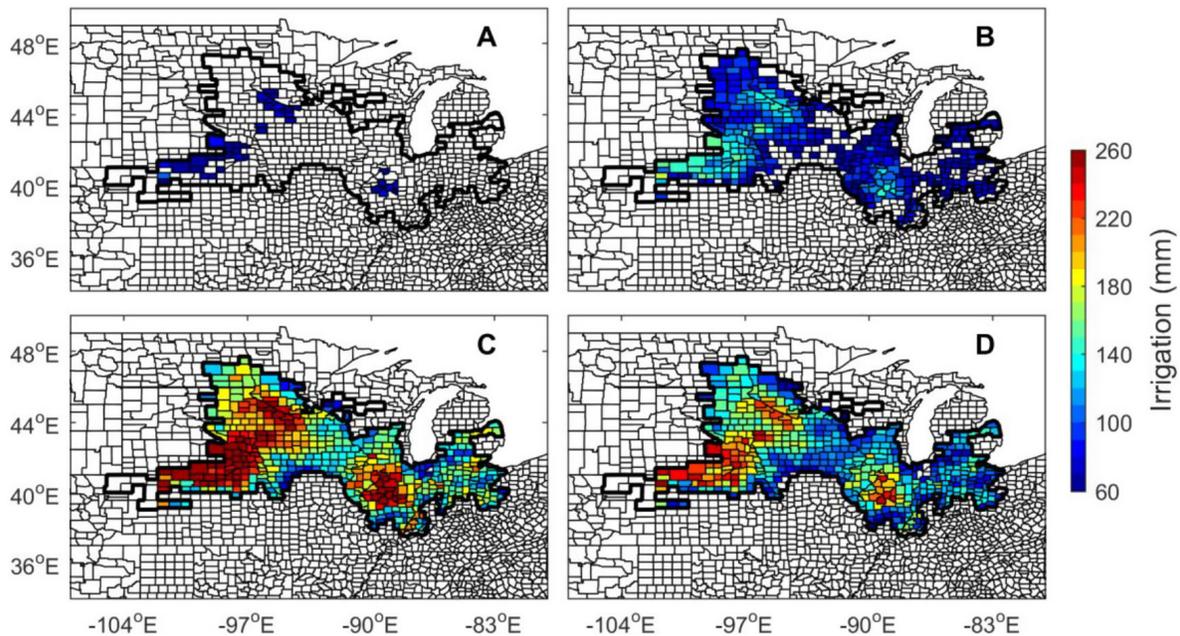


Fig. 4. (A) Projected area (by county) and amount of irrigation under current environmental conditions and current maize yields (irrigated area: 8140 km²; total irrigated water volume: 0.57×10^{10} m³); (B) projected area (by county) and amount of irrigation under current maize yields but with atmospheric VPD projected for 2050 (irrigated area: $563,000 \pm 92,000$ km²; total irrigated water volume: $5.27 \pm 1.23 \times 10^{10}$ m³); (C) projected area (by county) and amount of irrigation under projected future yields (40% increase) and VPD for 2050 (irrigated area: $776,000 \pm 27,000$ km²; total irrigated water volume: $13.8 \pm 1.7 \times 10^{10}$ m³); and (D) projected area (by county) and amount of irrigation under projected future yields and VPD for 2050, but with an 11.1% increase in WUE from reduced stomatal conductance (irrigated area: $760,000 \pm 52,000$ km²; total irrigated water volume: $10.8 \pm 1.6 \times 10^{10}$ m³). Only areas with irrigation of >60 mm during the growing season are shown. The area indicated on the map currently produces 75% of U.S. maize. Projected area and amount of irrigation varied depending on the climate model used to calculate future VPD (Appendix S1: Figs. S6, S7, S8).

Cousins 2018). At the level of whole plant canopies, changes in leaf orientation and the vertical distribution of leaf absorptance governed by chlorophyll content can improve WUE by redistributing light from the top of the canopy to closer to the soil where photosynthesis is light limited but higher humidity would reduce transpiration (Drewry et al. 2014, Long et al. 2015). At the landscape scale, soil amendments such as biochar (Jeffery et al. 2011), and soil and crop management practices, such as minimum tillage and crop residue management, can further improve WUE by reducing soil evaporation or runoff (Hatfield et al. 2011).

In regions where agriculture is supported by rain alone, a concerted effort to improve WUE may be necessary to maintain current maize

yields and the realization of even higher maize yields as temperature and atmospheric VPD continue to rise. Indeed, without high WUE the production of high biomass energy crops may also require greatly increasing the area and amount of irrigation, further intensifying competition for limited water resource.

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