



RESEARCH LETTER

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Key Points:

- Observations and numerical simulations both suggest that agricultural intensification has cooled temperatures and enhanced rainfall
- Agricultural intensification has been a larger forcing of regional climate change during the summer than rising greenhouse gas emissions
- Inclusion of agricultural intensification in next-generation climate models is warranted for more accurate simulations and attribution

Supporting Information:

- Supporting Information S1
- Movie S1

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Twentieth Century Regional Climate Change During the Summer in the Central United States Attributed to Agricultural Intensification

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Abstract Both land use changes and greenhouse gas (GHG) emissions have significantly modified regional climate over the last century. In the central United States, for example, observational data indicate that rainfall increased, surface air temperature decreased, and surface humidity increased during the summer over the course of the twentieth century concurrently with increases in both agricultural production and global GHG emissions. However, the relative contributions of each of these forcings to the observed regional changes remain unclear. Results of both regional climate model simulations and observational analyses suggest that much of the observed rainfall increase—as well as the decrease in temperature and increase in humidity—is attributable to agricultural intensification in the central United States, with natural variability and GHG emissions playing secondary roles. Thus, we conclude that twentieth century land use changes contributed more to forcing observed regional climate change during the summer in the central United States than increasing GHG emissions.

1. Introduction

Over the last century, the world has experienced unprecedented growth in cropland area and productivity (Pielke et al., 2011; Ramankutty & Foley, 1999). As part of this expansive agricultural development, the Corn Belt of the central United States (Figure 1a and Figure S1 in the supporting information)—one of the most productive agricultural areas in the world (Guanter et al., 2014; Mueller et al., 2016)—experienced major increases in both corn and soybean production. For example, from 1950 to 2010, the amount of corn harvested annually in the Corn Belt increased by 400%, from 2 billion to 10 billion bushels (National Agricultural Statistics Service, 2016) (Figure 2b and Movie S1). These large-scale land use modifications likely affected atmospheric processes, as changes in rain-fed and irrigated cropland have previously been shown to influence climatic variables such as evapotranspiration (Adegoke et al., 2003; Cook et al., 2015; Harding & Snyder, 2012; Huber et al., 2014; Im, Marcella, et al., 2014; Jin & Miller, 2010; Lo & Famiglietti, 2013; Mahmood et al., 2013; Ozdogan et al., 2010; Qian et al., 2013; Wei et al., 2013), temperature (Adegoke et al., 2003; Alter et al., 2015; Barnston & Schickedanz, 1984; Cook et al., 2015; Harding & Snyder, 2012; Haugland & Crawford, 2005; Huber et al., 2014; Im, Marcella, et al., 2014; Jin & Miller, 2010; Kueppers et al., 2007; Mahmood et al., 2013; Mueller et al., 2016; Qian et al., 2013), humidity (Adegoke et al., 2003; Cook et al., 2015; Harding & Snyder, 2012; Haugland & Crawford, 2005; Huber et al., 2014; Lo & Famiglietti, 2013; Mahmood et al., 2008; Qian et al., 2013), and precipitation (Alter et al., 2015; Barnston & Schickedanz, 1984; Cook et al., 2015; DeAngelis et al., 2010; Harding & Snyder, 2012; Huber et al., 2014; Im, Marcella, et al., 2014; Lo & Famiglietti, 2013; Mueller et al., 2016; Qian et al., 2013; Stidd, 1975; Wei et al., 2013). Given these established linkages, one would expect that these historical increases in crop production have impacted regional climate in the central United States.

Indeed, major changes in regional climate occurred simultaneously with agricultural intensification in the central United States over the course of the twentieth century. From 1910 to 1949 (preagricultural development, pre-DEV) to 1970–2009 (full agricultural development, full-DEV), the central United States experienced large-scale increases in rainfall of up to 35% and decreases in surface air temperature of up to 1°C during the boreal summer months of July and August (Figures 1b, 1c, and S2), when crop water use in the Corn Belt is at its peak (DeAngelis et al., 2010). The absolute magnitude of the pre-DEV to full-DEV increase in July–August rainfall is the largest in the world (Figure S3), and the magnitude of the concurrent decrease in temperature is

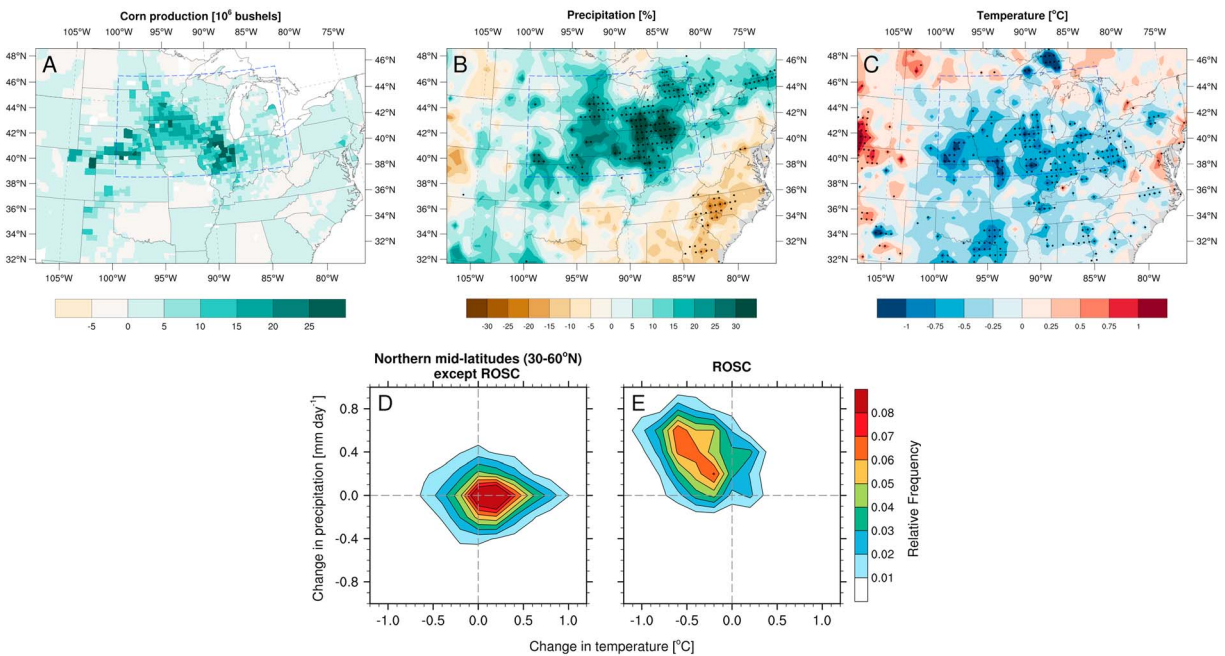


Figure 1. Observed spatial changes in regional climate and agricultural variables. Historical differences in (a) corn production, (b) July–August precipitation, and (c) July–August surface air temperature from before agricultural development (pre-DEV, 1910–1949) to full agricultural development (full-DEV, 1970–2009). The blue dotted line encloses the region where a large proportion of grid cells experienced statistically significant increases in observed rainfall (region of significant change—ROSC) according to the Kolmogorov-Smirnov test ($N = 40$, $p = 0.05$, significance indicated by black dots). Comparison of historical changes in July–August surface air temperature (horizontal axis) and precipitation (vertical axis) for grid cells in (d) the northern midlatitudes (30–60°N), excluding the ROSC, and (e) the ROSC, using the data from Figures S3 and S4.

only matched in eastern China (Figure S4). Furthermore, the central United States is one of the few regions in the northern midlatitudes that has experienced a combination of increasing rainfall and decreasing temperature over the aforementioned time period (Figures 1d and 1e), which conflicts with expectations from climate change projections for the end of the 21st century (i.e., warming and decreasing rainfall) (Melillo et al., 2014) but is likely consistent with expectations from denser vegetation (DeAngelis et al., 2010; Mueller et al., 2016).

Since these major increases in crop productivity and changes in regional climate are generally collocated in time and space over the central United States, we question whether the two phenomena are linked in a causal relationship. Recent studies connecting agricultural intensification to observed decreases in extreme temperatures in the central United States (Mueller et al., 2016) and other intensely cropped regions of the world (Mueller et al., 2017) add evidence to our hypothesis that historical agricultural intensification has affected regional summer climate in this area. However, major increases in anthropogenic greenhouse gas (GHG) emissions over the same time period (Intergovernmental Panel on Climate Change, 2013; Melillo et al., 2014) may have also been an important forcing of these observed changes. Therefore, we investigated these two potential forcings separately:

We conducted an ensemble of model simulations to determine the sensitivity of regional climate to agricultural intensification, and we analyzed the results of standardized simulations with global climate models to determine the regional impacts of GHG emissions and other nonagricultural forcings. Finally, we compared both sets of model results to observational analyses to determine which forcing was the more important contributor to these historical changes.

2. Results

2.1. Observational Data

We first investigate the relationship between cropland productivity and climate variables by comparing observational time series of cropland, rainfall, temperature, and humidity (Text S1). The time series indicate simultaneous increases in cropland productivity, rainfall, and specific humidity in the central United States during July–August, with a concurrent decrease in surface air temperature (Figures 2 and S5). Since

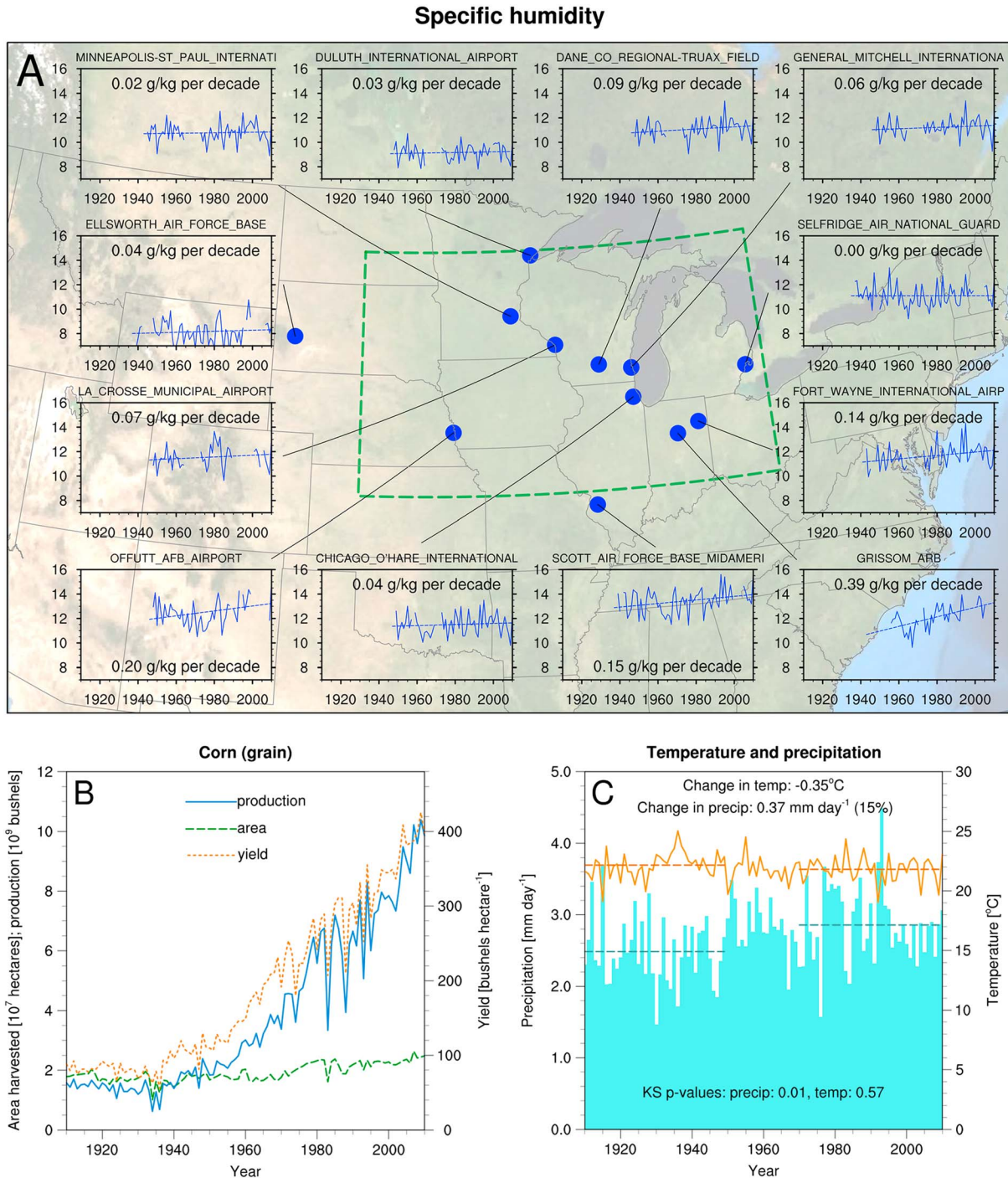


Figure 2. Observed temporal changes in regional climate and agricultural variables. Temporal evolution of (a) July–August surface specific humidity, (b) cropland production, harvested area, and yield for corn in the Corn Belt of the central United States, and (c) July–August precipitation (blue bars) and surface air temperature (orange line) over the ROSC (dotted green line in Figure 2a, see Figure 1 for definition). For Figure 2c, the *p* values for the Kolmogorov-Smirnov test ($N = 40$) comparing pre-DEV (1910–1949) and full-DEV (1970–2009) time periods are located above the horizontal axis. The data in Figure 2c are July–August mean monthly values of temperature and precipitation derived from the University of Delaware (UDel) terrestrial air temperature and precipitation: Monthly and annual time series (V3.01) data set (Willmott & Matsuura, 2015a, 2015b).

decreases in temperature and increases in atmospheric moisture have previously been found over areas of irrigated (i.e., high-productivity) agriculture (Adegoke et al., 2003; Brown & DeGaetano, 2013; Cook et al., 2015; Huber et al., 2014; Qian et al., 2013), it seems probable that these observed climatic changes have been influenced by historical increases in crop productivity within the central United States.

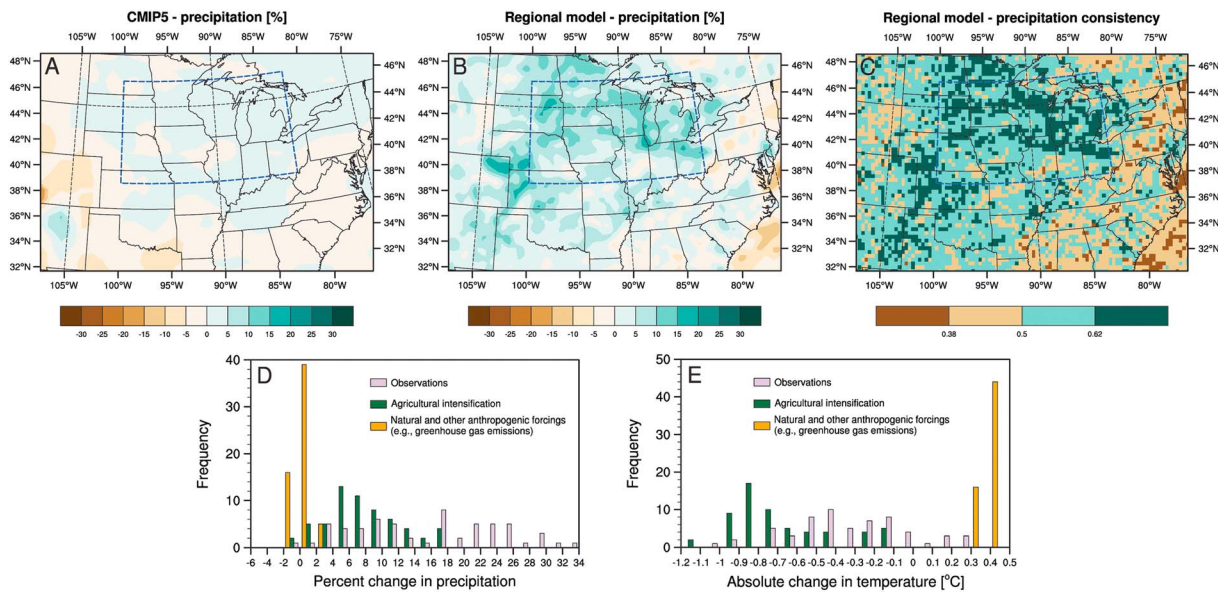


Figure 3. Simulated differences in precipitation and temperature due to agricultural intensification and nonagricultural forcings. (a) Differences in July–August precipitation from pre-DEV (1910–1949) to full-DEV (1970–2005) for an ensemble of historical simulations in the Coupled Model Intercomparison Project 5 (CMIP5) suite of global climate models that does not account for historical land use changes (historical CMIP5 simulations end in 2005), (b) percent change in precipitation simulated by the regional climate model due to agricultural intensification, (c) fraction of model years that experienced precipitation enhancement due to agricultural intensification in the regional climate model (dark colors indicate significance according to the chi-square test [$N = 150, p = 0.05$]), and (d) a histogram of percent change in precipitation from pre-DEV to full-DEV for observational data (Figure 1b, light purple), regional climate model output (Figure 3b, green), and CMIP5 output (Figure 3a, orange) within the ROSC (dotted blue line in Figures 3a–3c, see Figure 1 for ROSC definition). The results are interpolated to a box with 6×10 grid cells covering the ROSC ($N = 60$, see Text S1 for details). (e) Same as Figure 3d, but for absolute change in surface air temperature (observations, Figure 1c; regional model, Figure 4b; and CMIP5, Figure 4a).

2.2. Regional Climate Model Simulations

To better determine whether these observational trends are rooted in agricultural changes, we used a regional climate model to conduct an ensemble of five 30 year simulations (Text S1) with enhanced photosynthesis over cropland (Figure S6) to serve as a proxy for agricultural intensification. This set of simulations was then compared to a control simulation with no agricultural intensification. The difference between these two sets of simulations represents the theoretical effect of agricultural intensification on regional climate (see Text S1 for model evaluation information).

The results of the simulations indicate a widespread increase in summer rainfall caused by agricultural intensification in the central United States. Ensemble mean increases in July–August rainfall of 5–15% (0.15–0.45 mm/d) occur in a large swath from the Texas Panhandle north to the Canadian border and east to Ohio, with isolated values approaching 20% (0.60 mm/d) (Figures 3b and S7). Over the region that has experienced significant increases in observed rainfall (region of significant change—ROSC), the mean rainfall increase is ~7% (0.20 mm/d) for the simulations and ~15% (0.37 mm/d) for the observations (see Figure 3d for a histogram of these changes). Thus, it seems that agricultural intensification has been a major contributor to the observed increase in summer rainfall in the central United States.

Strikingly, these increases in rainfall are also very consistent: Agricultural intensification enhances simulated rainfall across the aforementioned swath in the central United States during at least 62% of the 150 ensemble years (significant at the 5% level using the chi-square test; Text S1) (Figure 3c). In the observational data, a similar consistency in precipitation enhancement is evident when comparing the pre-DEV and full-DEV time periods (Text S1). This suggests that the changes in rainfall due to agricultural intensification are not the result of occasional increases but instead are indicative of a more systematic change in the summer rainfall regime of the central United States.

2.3. Global Climate Model Comparisons

On the other hand, it is possible that other forcings—both natural (e.g., variations in sea surface temperature (SST) and atmospheric circulations) and anthropogenic (e.g., enhanced GHG emissions)—have contributed

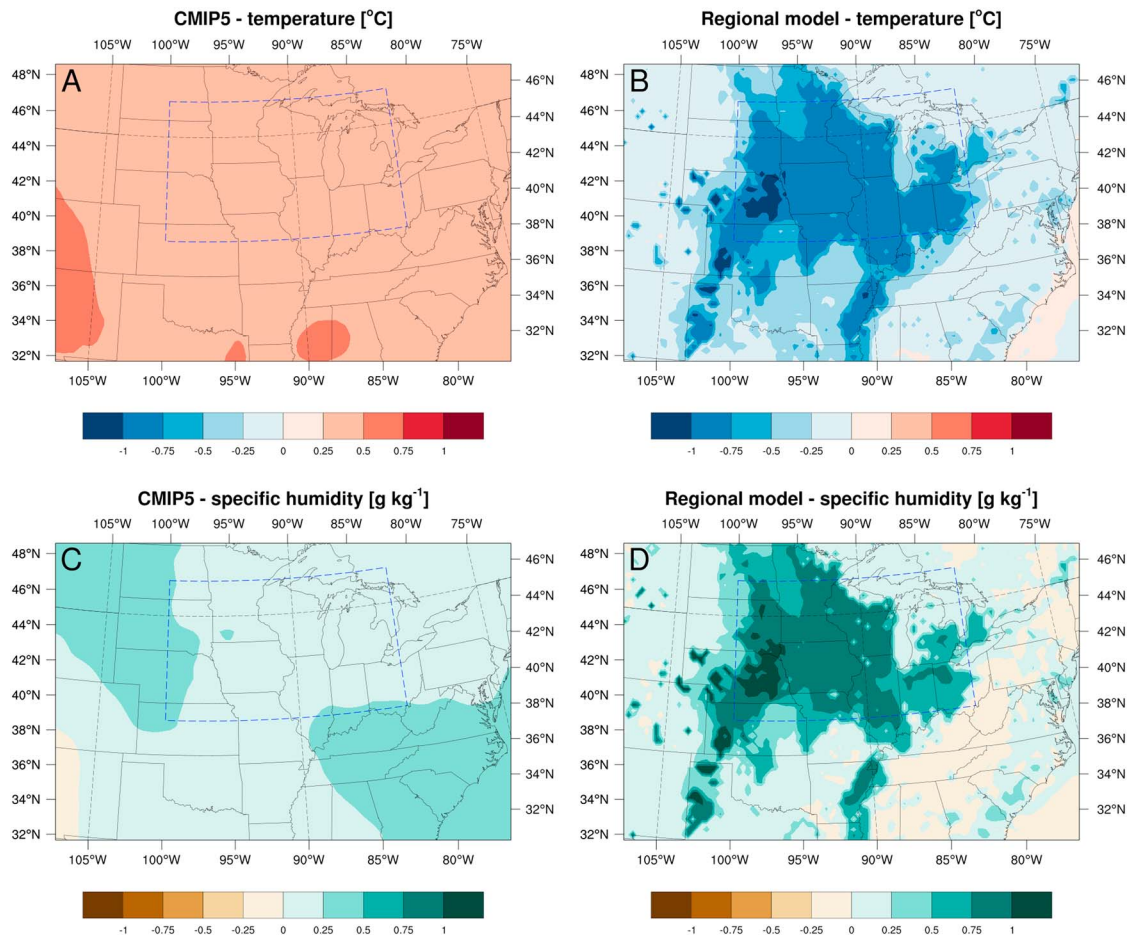


Figure 4. Simulated differences in surface air temperature and humidity due to agricultural intensification and nonagricultural forcings. Differences in (a) surface air temperature and (c) surface specific humidity from pre-DEV (1910–1949) to full-DEV (1970–2005, historical CMIP5 runs end in 2005) for an ensemble of historical simulations in the CMIP5 suite of global climate models that does not account for historical land use changes. Differences in (b) surface air temperature and (d) surface specific humidity due to agricultural intensification in the regional climate model.

to the observed rainfall enhancement in the central United States. To evaluate the role of these additional forcings, we analyzed the results of standardized historical simulations from general circulation models in the Coupled Model Intercomparison Project 5 (CMIP5, Taylor et al., 2012) (Table S1), which include the combined effects of GHG emissions and natural and other anthropogenic forcings (hereafter referred to as just “GHG emissions”). The global coverage of the CMIP5 models can better capture the climatic effects of these forcings. We only analyzed CMIP5 models that do not include historical land use changes so as to better isolate the impacts of the nonagricultural forcings on regional climate. The output from this subset of CMIP5 models indicates only small changes in rainfall (between -2% and $+4\%$) during the summer in the central United States, which are much smaller than the frequency distributions of rainfall change from both the observational data and the agricultural intensification simulations (Figures 3a and 3d). This implies that GHG emissions may not have been a major driver of the observed changes in summer rainfall.

Additionally, we compared the spatial variability of changes in temperature and humidity between the regional model and CMIP5 models to see whether these secondary variables are more influenced by agricultural intensification or GHG emissions. The regional model simulates decreases in temperature and increases in humidity during the summer (Figures 4b and 4d) that are consistent with the observed changes in these variables (Figures 2a and 3e). However, the CMIP5 results instead show an increase in temperature and a much subdued increase in specific humidity (Figures 3e, 4a, and 4c), which may be due to GHG-induced warming and subsequent increases in the water vapor holding capacity of the atmosphere, respectively. Thus, it seems that GHG emissions do not contribute greatly to the regional changes in summer climate that have been observed in the central United States.

2.4. Sea Surface Temperature as a Potential Forcing

However, CMIP5 simulations are not constrained by historical observed SST changes (Taylor et al., 2012), and previous work has indicated a strong correlation between historical SST decadal variability in the Pacific Ocean and summer rainfall in the central United States (Wang et al., 2009). Thus, we analyzed the temporal evolution of the Pacific Decadal Oscillation (PDO)—a measure of SST variability in the Pacific Ocean—and rainfall in the Corn Belt of the central United States to see if they exhibited similar trends. The time series produced by this analysis shows that while anomalies in the PDO index (Joint Institute for the Study of the Atmosphere and Ocean, 2016) and Corn Belt rainfall (National Centers for Environmental Information (NCEI), 2016a) for July–August were negatively correlated during approximately the first two thirds of the twentieth century (1915–1969, $r = -0.66$), they became positively correlated during approximately the last third of the twentieth century (1970–2005, $r = 0.73$) (Figure S8). This result suggests that natural variability of the PDO cannot explain the observed, long-term enhancement of rainfall over the Corn Belt. In fact, this inconsistency in the PDO-rainfall relationship illustrates that there was likely an additional forcing, such as agricultural intensification, that enhanced summer rainfall in the central United States during the last third of the twentieth century.

3. Mechanisms and Future Work

Following is a mechanistic discussion that describes potential pathways from the observed increases in crop production (Figure 2b), crop yield (Figure 2b), and net primary productivity (e.g., Mueller et al., 2017) to simulated changes in temperature, humidity, and rainfall that are based on results from our modeling experiments:

First, we assume that the aforementioned observed increases in crop productivity were associated with consistent increases in the rate of photosynthesis. Within the regional climate model, an increase in photosynthesis for cropped areas leads to a decrease in stomatal resistance within those areas. This allows more water vapor to be released to the atmosphere through evapotranspiration (ET), specifically through transpiration. This increased flow of water out of the plants results in an increase in atmospheric moisture (humidity) over the same areas. Regarding the energy budget, the latent heat flux increases in tandem with ET, but the sensible heat flux decreases, resulting in temperature decreases over the cropped areas.

From here, we hypothesize two possible modes of influence of agricultural intensification on rainfall:

The first pathway involves an increase in moist static energy (MSE) near the surface. Changes in MSE are positively correlated with changes in both temperature and humidity. However, since temperature and humidity exhibit changes of opposite sign due to agricultural intensification, it is necessary to calculate the terms in the MSE equation to determine whether MSE in general would increase or decrease:

$$\text{MSE} = C_p T + gz + L_v r, \quad (1)$$

where

C_p specific heat of air at constant pressure ($\text{kJ kg}^{-1} \text{K}^{-1}$),

T air temperature (K),

g gravitational acceleration (m s^{-2}),

z height above some reference level (m),

L_v latent heat of vaporization for water (kJ kg^{-1}), and

r water vapor mixing ratio (kg kg^{-1}).

In equation (1), the terms $C_p T$ and $L_v r$ represent contributions from temperature and moisture, respectively. According to Figure 4, temperature exhibits an average change of ~ -1 K over cropland due to agricultural intensification, while specific humidity (approximately equivalent to water vapor mixing ratio) exhibits an average change of $\sim +1$ g kg^{-1} over cropland due to agricultural intensification. Using standard values of $1.0 \text{ kJ kg}^{-1} \text{K}^{-1}$ for C_p and 2260 kJ kg^{-1} for L_v , we obtain approximate MSE contributions of -1 kJ kg^{-1} for the temperature term and $+2.26 \text{ kJ kg}^{-1}$ for the moisture term. Since the positive moisture contribution has a larger magnitude than the negative temperature contribution, MSE would increase over cropland as a result of agricultural intensification. This excess MSE near the surface would likely enhance moist

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convection and rainfall (Eltahir, 1998; Eltahir & Pal, 1996; Pal & Eltahir, 2001), which would lead to generally more summer precipitation in the vicinity of the more productive croplands.

A second potential pathway deals with moisture recycling. Since atmospheric moisture increases in the planetary boundary layer as a result of agricultural intensification, it is possible that the additional moisture will eventually fall out as rain over a nearby area, causing an increase in precipitation over or near the intensified agriculture. This water would eventually recycle back into the atmosphere and potentially cause increased rainfall even farther downwind, resulting in potential crop-induced precipitation remote from the original cropped location.

More comprehensive analysis of these potential mechanisms would be ideal for future work on this topic. It would also be instructive to include agricultural intensification in future studies of land use/land cover change that investigate the impacts of modern land management on regional climate. Furthermore, adding a more comprehensive investigation of irrigation impacts on regional climate in the central United States to our simulations, perhaps testing different irrigation schemes and time-evolving irrigation extent and application amount, could provide additional information on the relationship between intensification and irrigation. Finally, it should be noted that the simulations in this study essentially represent sensitivity experiments for particular forcings (GHG and agricultural intensification), so it would be prudent to conduct more integrated observational and modeling experiments that can corroborate the results of this study.

4. Conclusions

Overall, the combination of observational and model-derived evidence points to a tangible, systematic influence of agricultural intensification on regional climate during the summer in the central United States. There are numerous potential implications of these findings: (1) this study provides evidence that agricultural intensification can be a more important driver of observed regional climate change than GHG emissions (Table S2); (2) however, cooling due to agricultural intensification in the central United States may have masked warmer temperatures that would have otherwise resulted from increasing GHG emissions (Figure 4); (3) the knowledge gained from this study encourages the inclusion of crop productivity in next-generation climate models to more accurately simulate past and future climate and improve attribution studies; (4) crop-induced rainfall in the Corn Belt may have enabled further agricultural intensification by filling soil moisture deficits that would have otherwise occurred as a result of the large increase in crop evapotranspiration; (5) since vast tracts of land worldwide have experienced similar booms of agricultural productivity in recent decades, it is possible that other areas of the world have experienced similar climatic effects due to agricultural intensification, especially in light of recent observational connections between extreme temperatures and agricultural intensification in other intensely cropped regions (Mueller et al., 2017); and (6) recognition of this relationship between crops and climate adds complexity to our existing framework of hydrological, agricultural, and economic sustainability. Because of all these considerations, the effects of agricultural intensification on regional climate deserve consideration in plans to mitigate and adapt to future climate change in the United States and worldwide.

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