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Quantifying irrigation cooling benefits to maize yield in the US Midwest

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Abstract

Irrigation is an important adaptation strategy to improve crop resilience to global climate change. Irrigation plays an essential role in sustaining crop production in water-limited regions, as irrigation water not only benefits crops through fulfilling crops' water demand but also creates an evaporative cooling that mitigates crop heat stress. Here we use satellite remote sensing and maize yield data in the state of Nebraska, USA, combined with statistical models, to quantify the contribution of cooling and water supply to the yield benefits due to irrigation. Results show that irrigation leads to a considerable cooling on daytime land surface temperature (−1.63°C in July), an increase in enhanced vegetation index (+0.10 in July), and 81% higher maize yields compared to rainfed maize. These irrigation effects vary along the spatial and temporal gradients of precipitation and temperature, with a greater effect in dry and hot conditions, and decline toward wet and cool conditions. We find that 16% of irrigation yield increase is due to irrigation cooling, while the rest (84%) is due to water supply and other factors. The irrigation cooling effect is also observed on air temperature (−0.38 to −0.53°C) from paired flux sites in Nebraska. This study highlights the non-negligible contribution of irrigation cooling to the yield benefits of irrigation, and such an effect may become more important in the future with continued warming and more frequent droughts.

KEYWORDS
cooling, irrigation, LST, maize yield, water

1 | INTRODUCTION

Global climate changes, characterized by rising temperature, increasing severity and frequency of droughts and heatwaves, pose a great risk to agricultural production and threaten global food security (Rosenzweig et al., 2013; Trnka et al., 2014; Zhao et al., 2017). As an effective adaptation strategy to improve crop resilience to climate change (Marshall, Aillery, Malcolm, & Williams, 2015), irrigation plays a critical role in sustaining crop production and constitutes an essential component of modern agriculture, especially in arid and semi-arid regions where crop growth is limited by water (Elliott et al., 2014). Irrigation, accounting for only 20% of global cropland, produces 40%–45% of the world's food (Döll & Siebert, 2002). Although irrigation is necessary to maintain crop productivity and feed the growing populations, irrigation may lead to other serious environmental consequences such as increasing water scarcity, groundwater depletion, and salinization in many parts of the world (Beltrán, 1999; Elliott et al., 2014; Liu et al., 2017; Marshall et al., 2015) and important climate feedbacks (Kueppers, Snyder, & Sloan, 2007; Mahmood et al., 2006; Mueller et al., 2015; Sacks, Cook, Buenning, Levis, &

Helkowski, 2008). Therefore, a quantitative understanding of irrigation effects on crop yield and their underlying processes is pivotal to promote sustainable irrigation practices to ensure both food security and environmental sustainability (West et al., 2014).

Irrigation effects on crops have been extensively studied and existing knowledge suggests that irrigation benefits crops from several aspects. With irrigation, crops become more productive than those under rainfed conditions, as increases in leaf area/biomass and evapotranspiration collectively translate into higher crop yields (Grassini, Yang, & Cassman, 2009; Oweis, Zhang, & Pala, 2000; Payero, Tarkalson, Irmak, Davison, & Petersen, 2008). Furthermore, irrigation makes crop yield less dependent on climate, buffering yield variability from climate fluctuation (Li, Guan, Yu, et al., 2019; Shaw, Mehta, & Riha, 2014; Troy, Kipgen, & Pal, 2015). Irrigation also improves crop yield stability by partially offsetting the negative impacts of water stress under extreme drought and warming conditions (Tack, Barkley, & Hendricks, 2017; Troy et al., 2015; Zaveri & Lobell, 2019). These various benefits of irrigation are underpinned by the two key mechanisms, water supply and cooling, which reduce the effects of drought and heat stress on crop growth. The primary goal of irrigation is to supply an adequate amount of water when rainfall is not sufficient or timely to meet the water demands of crops. Such issues regarding water supply are not limited to arid regions. Even in relatively humid regions with sufficient total precipitation, irrigation increases yield relative to rainfed crops as it compensates for intra-seasonal rainfall variability (Grassini et al., 2009) or supplements precipitation during sensitive crop growth stages (Katerji, Mastrorilli, & Rana, 2008).

Irrigation also increases soil evaporation and crops' transpiration, and thus creates a local cooling effect that takes place during the irrigation season (Lobell, Bonfils, Kueppers, & Snyder, 2008; Siebert, Webber, Zhao, & Ewert, 2017; Szilagyi, 2018). Several empirical and modeling studies have found significant cooling over intensively irrigated areas such as the West (Kueppers et al., 2007) and Midwest US (Huber, Mechem, & Brunsell, 2014; Mahmood et al., 2006), North China (Wu, Feng, & Miao, 2018), Northeast China (Yang, Huang, & Tang, 2020; Zhu, Liang, & Pan, 2012), and India (Douglas, Beltrán-Przekurat, Niyogi, Pielke, & Vörösmarty, 2009). The cooling effect is greater in reducing maximum temperature (Bonfils & Lobell, 2007) and becomes more pronounced during hot days, where irrigation decreases annual maximum temperature by −0.78 K, a four times larger effect than on mean temperature owing to increased irrigation application (Thiery et al., 2017). Since crop yield is highly sensitive to high temperature and vapor pressure deficit (Lobell et al., 2013), this cooling effect benefits crops through reducing heat stress (Siebert, Ewert, Rezaei, Kage, & Graß, 2014; Siebert et al., 2017) and evaporative demand (Nocco, Smail, & Kucharik, 2019), and therefore mitigates the impacts of extreme heat (Vogel et al., 2019). In particular, irrigation cooling can shift the high temperature thresholds of crops beyond which yield declines so that crops become less susceptible to extreme weather (Carter, Melkonian, Riha, & Shaw, 2016; Lobell et al., 2013; Schlenker & Roberts, 2009; Troy et al., 2015).

Although both water supply and cooling are responsible for yield gain due to irrigation (Walker, 1989), most attention focused on the water supply effect over the past several decades (Szilagyi, 2018). A number of field and controlled experiments have examined the effects of drought stress at different phenological stages on crop growth/yield processes (Çakir, 2004; Denmead & Shaw, 1960; Holt & Timmons, 1968); how different irrigation treatments (amount, timing, and duration) affect crop yield and water use efficiency (Eck, 1986; Hatlitligil, Olson, & Compton, 1984; Payero et al., 2008), and the interactive effects of irrigation and nitrogen (Al-Kaisi & Yin, 2003; Hatlitligil et al., 1984). Several crop modeling studies assessed potential yield gain under different irrigation scenarios (Grassini et al., 2009), historical and future irrigation impacts on regional water balance (Leng, Huang, Tang, & Leung, 2015; Zhao et al., 2015), and the effectiveness of various adaptation strategies on crop production (Hernandez-Ochoa et al., 2019). However, the cooling effect of irrigation on crop yield has been largely overlooked in the literature, and the separate contributions of water supply and cooling to yield benefit of irrigation remain to be quantified, especially over a large scale. These unresolved issues will be even more important under future climate changes where both water and heat stresses are anticipated to become more severe (Deryng, Conway, Ramankutty, Price, & Warren, 2014; Mazdiyasni & AghaKouchak, 2015).

Nevertheless, separate quantification of these effects is difficult for field studies as plant water status and temperature are inherently coupled (Prasad et al., 2008). Under controlled environments, the separation might be possible with carefully designed experiments but results obtained in this way may not be representative of a variety of irrigation and climate conditions in the field. Moreover, given the substantial heterogeneities in crop system and irrigation practice, it is unclear how much the findings from these plant-level studies are transferable to other locations and over larger spatial scales (e.g., administrative or regional level). Satellite remote sensing provides a unique opportunity to quantify irrigation effects over the large scale with high spatial details. Existing satellite data products deliver a wide range of useful crop-related variables including Enhanced Vegetation Index (EVI) for crop biomass and yield (Johnson, 2014), land surface temperature (LST) for heat and drought stress (Siebert et al., 2014), and irrigated cropland mapping (Xie, Lark, Brown, & Gibbs, 2019). A wealth of satellite information, combined with crop yield responses derived from statistical model with a large sample of surveyed yield data, allows attribution of crop yield to different environmental drivers at the regional scale under varying climate conditions. These research efforts will help assess the benefit and trade-off of irrigation practice at the administrative level to inform policymaking for agriculture and water resource management.

In this study, we aim to quantify irrigation effects on crops using multiple satellite and statistical data to determine the extent to which water supply and cooling contribute to yield benefits of irrigation at the regional scale. We first analyzed irrigation effects on crop growth and their spatial and temporal variations with satellite remote sensing and statistical crop yield data. Irrigation effects (including cooling and biomass/yield changes) were quantified by comparing LST, EVI, and crop yields between irrigated and rainfed maize. Next, we proposed a statistical method to quantify the separate contribution of water supply and cooling to yield benefits of irrigation. Our analysis focused on maize in the state of Nebraska because it is a major maize-producing state in the Midwest US with an extensive irrigation/precipitation gradient (Szilagyi, 2018). Nebraska produces 43 million Megatons of maize annually in ~4 million ha, ranking the third among US maize-producing states, with irrigated area accounting for ~58% and 65% of its total maize cropland and production, respectively (source: US Department of Agriculture National Agricultural Statistics Service [USDA-NASS], 2014–2018).

2 | MATERIALS AND METHODS

2.1 | Data

2.1.1 | MODIS remote sensing data

We used 8-day LST data (MYD11A2) at 1 km spatial resolution and 16-day EVI (MYD13Q1) data at 250 m spatial resolution as proxies of crop temperature and biomass. The LST and EVI data were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 from 2003 to 2016. The daytime and nighttime LSTs retrieved from the Aqua satellite approximate the maximum and minimum temperature of a day as the satellite has a local overpass time of 13:30 and 01:30, respectively. The LST data were used to quantify the irrigation cooling effect.

2.1.2 | Irrigation map and crop classification data

The 2005 Nebraska irrigation map produced by the Center for Advanced Land Management Information Technologies (CALMIT) at the University of Nebraska-Lincoln provides a field-level inventory of center pivot and other irrigation systems (e.g., flood irrigation) in Nebraska for the growing season of 2005. The irrigation systems were identified using Landsat 5 Thematic Mapper 30 m satellite imagery and Farm Service Agency 1m airborne orthoimagery (see more information at https://calmit.unl.edu/metadata-2005-nebraska-land-use-center-pivots-irrigation-systems). The irrigation map, originally provided in vector format, was converted to 30 m raster and then used in conjunction with maize maps extracted from Crop Data Layer (CDL) from 2003 to 2016 at 30 m to determine locations of irrigated and rainfed maize fields in Nebraska.

2.1.3 | Statistical crop yield data

The county-level crop yield and harvest area data in Nebraska were obtained from the USDA-NASS (https://quickstats.nass.usda.gov/), including crop yields for both irrigated and rainfed maize from 2003 to 2016. The unit of maize yield is bu/acre and can be converted to t/ha by multiplying a factor of 0.0628.

2.1.4 | Gridded and flux tower climate data

The gridded daily Parameter-elevation Relationships on Independent Slopes Model (PRISM) climate data from 2003 to 2016 include maximum air temperature and precipitation (ftp://prism.oregonstate.edu/), which represent the background climate conditions of the study area and are theoretically independent of cropland and irrigation. The PRISM climate data were used to analyze how irrigation effects vary with different climate conditions. The data originally had a spatial resolution of 4 km and were averaged to county level in our analysis.

To examine whether irrigation cooling effect is observable at the field level via air temperature, we used the daytime air temperature measurements ('TA_F_MDS' variable) of three maize flux sites (US-Ne1, Ne2, and Ne3) from AmeriFlux in Nebraska from 2001 to 2013 (Suyker & Verma, 2012; Suyker, Verma, Burba, & Arkebauer, 2005). NE1 is an irrigated maize site. NE2 is also an irrigated site where maize and soybean are rotated (maize in odd years during 2001–2009 and all years between 2010 and 2013). NE3 is a rainfed site with maize and soybean rotated (maize in all odd years during 2001–2013). By assuming these three sites are close in distance to share similar large-scale climate patterns, the paired differences between irrigated and rainfed sites such as Ne1–Ne3 and Ne2–Ne3 are indications of the irrigation effect on air temperature.

2.2 | Methods

2.2.1 | Extracting crop properties of irrigated and rainfed maize from remote sensing

In this study, the presence of irrigation facilities was treated as a proxy of irrigation practice in the field. Because specific information regarding the timing and amount of irrigation water application is unavailable, we assumed that producers will make optimized irrigation decisions to maximize their profit. Therefore, irrigation effect was quantified as the county-level differences in crop properties (i.e., LST, EVI, and crop yield) between irrigated and rainfed maize, which reflect the collective impact of irrigation on crops at a larger scale without differentiating specific irrigation treatments. Even though county-level irrigated and rainfed maize yields are readily available from NASS, their county-level LST and EVI values have to be extracted on Google Earth Engine following the data processing procedures described in Figure 1 (Steps 1–4).

The 2005 irrigation map was first overlaid with 2005 CDL data to extract irrigated and rainfed maize pixels at 30 m resolution (Step 1). These 30 m pixels were then spatially aggregated to create irrigated and rainfed maize masks at MODIS resolution with the majority method (1 km for LST and 250 m for EVI). The irrigated/rainfed maize masks were combined with MODIS LST/EVI data to extract their corresponding property values at the MODIS resolution (Step 2). With a Nebraska county map, the resulting LST/EVI pixels of irrigated/rainfed maize at MODIS resolution were then

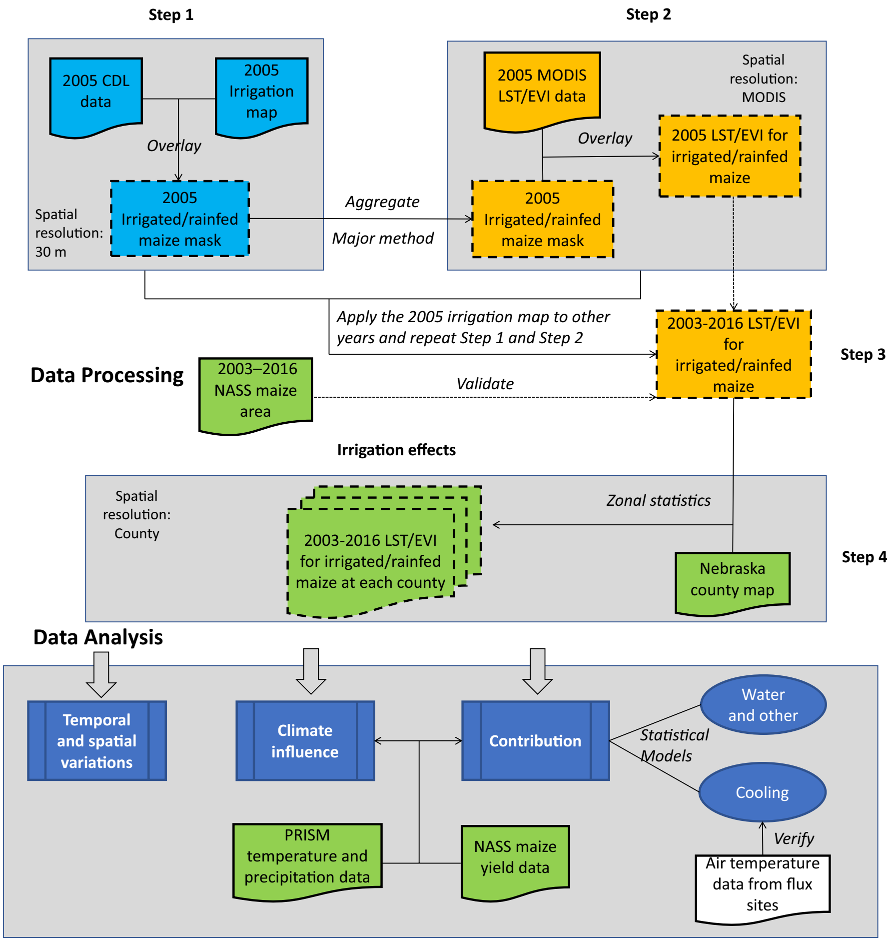

FIGURE 1 Summary of the data processing and analysis of this study. Boxes in blue, yellow, and green color represent spatial resolutions at 30 m, MODIS, and county level, respectively. CDL, Crop Data Layer; EVI, Enhanced Vegetation Index; LST, land surface temperature; MODIS, Moderate Resolution Imaging Spectroradiometer; NASS, National Agricultural Statistics Service

aggregated to county average values (Step 4). Through these steps, we obtained LST and EVI values of irrigated and rainfed maize for each county as well as their county-level differences in 2005 (because the irrigation map was produced only for 2005). To extend this method to work with other years which do not have their corresponding irrigation maps, we assumed that the 2005 irrigation map is also applicable to other years (Step 3). This assumption enabled us to eventually obtain county-level LST and EVI values of irrigated and rainfed maize throughout the study period (from 2003 to 2016, Steps 3 and 4). The processed satellite data together with county-level climate and yield data (green boxes in Figure 1) were used to quantify irrigation effect as described in Section 2.2.2.

Furthermore, to test the validity of above assumption, we compared irrigated and rainfed maize area derived under this assumption in other years with area statistics from NASS. If the assumption was not accurate, the derived maize harvest area of a given year would show a large bias against NASS statistics and would not be able to track temporal changes in harvest area. We found high correlations between these two from our county-level validation results for each year ($r = .99$ and .94 for irrigated and rainfed maize area from 2003 to 2016, respectively, see scatterplots in Figures S1 and S2). Moreover, the predicted irrigated/rainfed area summed at the state level can relatively well capture the interannual variations of NASS areas (Figure S3). These results supported the broad robustness of this assumption.

2.2.2 | Separation of cooling and water supply in yield benefit due to irrigation

Irrigated and rainfed crops differ in their responses to temperature. Although crop yields generally decline with increasing temperature, the declining yield pattern is more evident for rainfed than irrigated maize, implying a higher temperature sensitivity of the former (Figure 2a). Suppose a county grows both irrigated and rainfed maize in Figure 2b, the irrigated maize at point *A* would have a higher yield and a lower LST than the rainfed maize from the same county at point *D*. For rainfed maize, if a hypothetical cooling effect was applied (line *D*–*C*), its yield would move along its temperature response curve to increase from point *D* to point *B*, and the yield difference, denoted by line *B*–*C*, quantifies the cooling effect on yield. Although rainfed maize at point *B* has the same lower temperature as irrigated maize (point *A*), there is still a yield gap as denoted by line *A*–*B*. The yield gap under this condition is not caused by their temperature difference but reflects the water supply effect of irrigation. Therefore, the yield effect of irrigation (line *A*–*C*) can be effectively decomposed into the contribution from cooling (line *B*–*C*) and water supply (line *A*–*B*, it may include other factors, see Section 4).

The above concept can be implemented more rigorously with statistical models. The statistical model was constructed using monthly LST and precipitation from June to August as independent variables

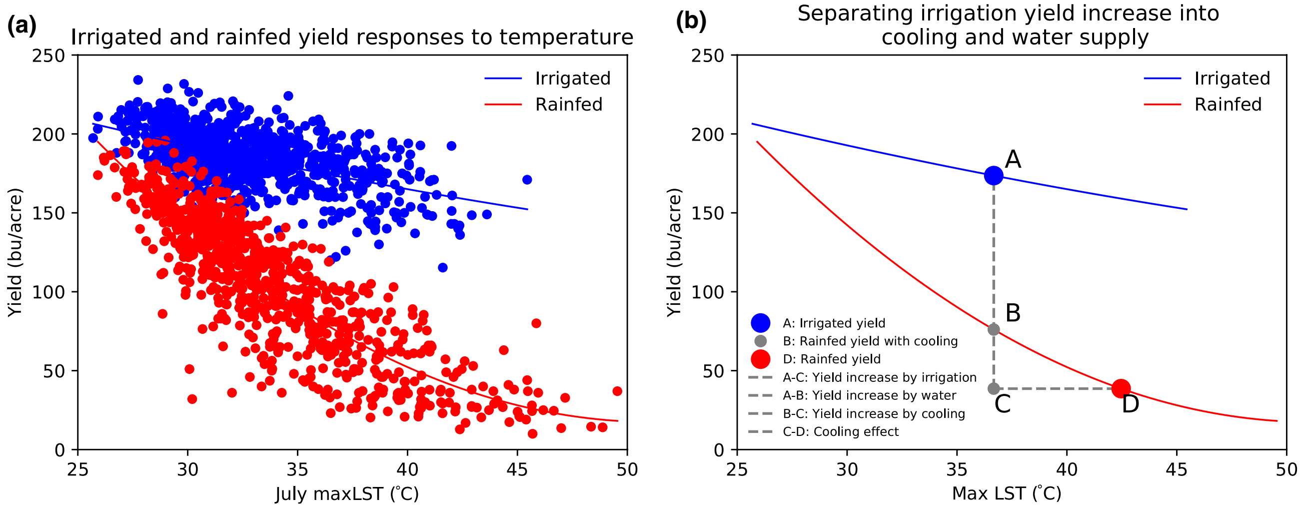

FIGURE 2 (a) Yield responses of irrigated and rainfed maize to July maximum land surface temperature (LST). (b) Conceptual diagram of separating the cooling and water supply effects in irrigation-induced yield increase

to predict county crop yield (Equation 1). Precipitation variables were included in the model to control yield co-variations with background precipitation conditions. The model configuration is shown below:

$$\text{Yield} = a \cdot \text{year} + \sum_{m=\text{June}}^{\text{Aug}} \left(b_m \cdot \text{LST}_m + c_m \cdot \text{LST}_m^2 + d_m \cdot P_m + e_m \cdot P_m^2 \right) + c_0, \quad (1)$$

where a, b, c, ..., e, and C_0 are estimated coefficients whose subscripts m denote month. The 'year' predictor was included to account for the long-term increasing yield trends due to improvements in management and technology. The quadratic LST and precipitation variables were included to account for the nonlinear crop yield response to climate (Li, Guan, Yu, et al., 2019; Schlenker & Roberts, 2009), which is a common technique used in statistical crop model studies (Blanc & Schlenker, 2017; Roberts, Braun, Sinclair, Lobell, & Schlenker, 2017). By training the model with rainfed and irrigated maize yield data, respectively, we would have two models, one for rainfed maize (Equation 2) and another one for irrigated maize (Equation 3):

$$\text{Rainfed maize model: Yield}_{\text{rain}} = f_{\text{rain}}(\text{LST}_{\text{rain}}, P), \quad (2)$$

$$\text{Irrigated maize model: Yield}_{\text{irr}} = f_{\text{irr}}(\text{LST}_{\text{irr}}, P), \quad (3)$$

where f_{rain} and f_{irr} are the fitted functions (i.e., the right-hand side of Equation 1) for rainfed and irrigated maize, respectively. The water supply effect is embedded in the function f_{irr}, as the predicted irrigated yield would be intrinsically higher than the predicted rainfed yield by f_{rain} even with the same climate input variables. These statistical models serve as a mathematical tool to emulate temperature response curves in Figure 2b. The rainfed and irrigated maize models after training can explain about 84% and 46% of spatiotemporal yield variations from 2003 to 2016, respectively (see Figure S4, and Tables S1 and S2 for estimated model coefficients). The relatively lower explanation power of irrigated model was expected as it reflects the fact that irrigated crop yield is more stable and less sensitive to climate variability (Li, Guan, Yu, et al., 2019; Shaw et al., 2014; Troy et al., 2015). The predicted yield difference (irrigated vs. rainfed) showed a high correlation with their actual yield differences (r = .86). This good model performance enables us to separate the irrigation effect on crop yield into cooling and water supply.

The cooling effect on yield, $\Delta\text{Yield}_{\text{cooling}}$, is defined as the hypothetical yield increase in rainfed maize if the same cooling as irrigated maize was applied. $\Delta\text{Yield}_{\text{cooling}}$ can be calculated as the predicted yield of irrigated LST with the rainfed model minus the predicted yield of rainfed LST with the rainfed model (Equation 4). Similarly, the water supply effect on yield, $\Delta\text{Yield}_{\text{water}}$, is defined as the yield increase if the same additional water as irrigated maize was applied to rainfed maize. It is can be calculated as the predicted yield of irrigated LST with the irrigated model minus the predicted yield of the same irrigated LST but with the rainfed model (Equation 5).

$$\Delta\text{Yield}_{\text{cooling}} = f_{\text{rain}}(\text{LST}_{\text{irr}}, P) - f_{\text{rain}}(\text{LST}_{\text{rain}}, P), \quad (4)$$

$$\Delta\text{Yield}_{\text{water}} = f_{\text{irr}}(\text{LST}_{\text{irr}}, P) - f_{\text{rain}}(\text{LST}_{\text{irr}}, P). \quad (5)$$

3 | RESULTS

3.1 | Irrigation effects on LST, EVI, and maize yield

The purpose of irrigation is to apply additional water to maintain soil moisture above a certain level to prevent crop water stress. This means that the applied amount of irrigation water (e.g., irrigation water demand) and its effect, by design, depend on climate conditions and therefore have seasonal and regional variations. The irrigation effect on crop was manifested as the differences between rainfed and irrigated maize, which can be seen in individual counties

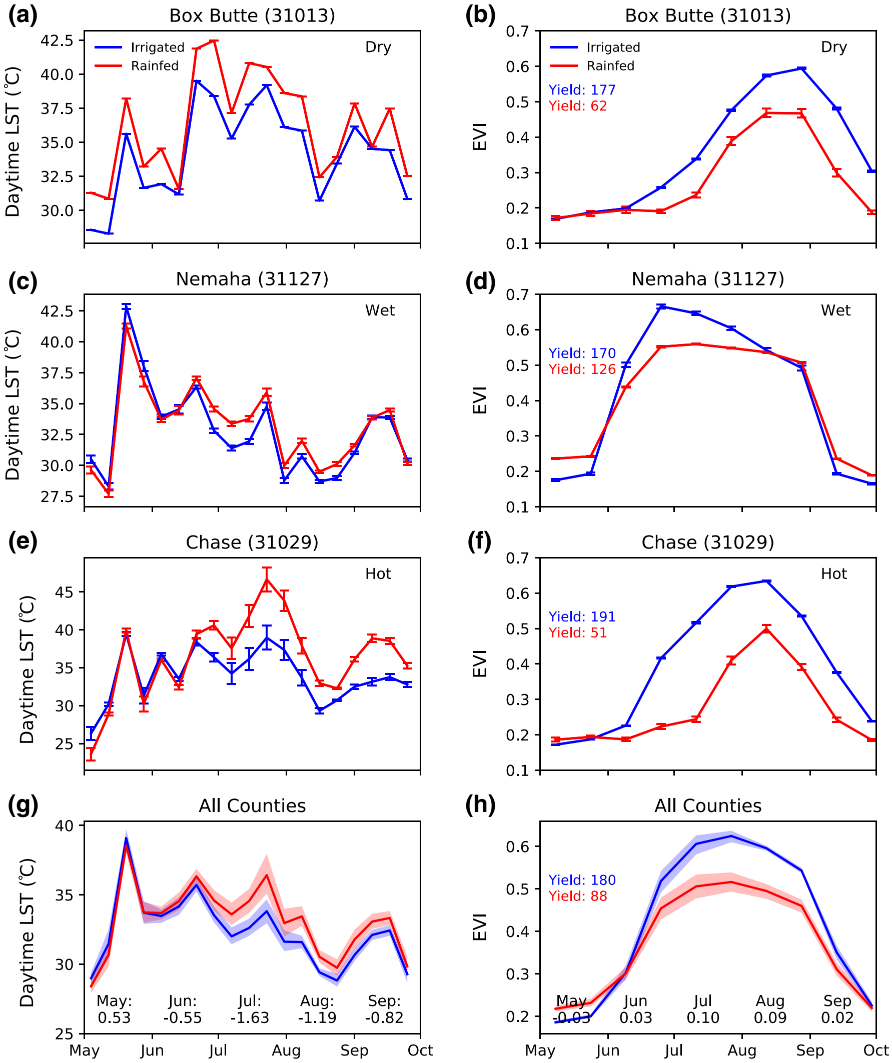

FIGURE 3 Irrigation effects on maize land surface temperature (LST) and Enhanced Vegetation Index (EVI) in three selected counties (a–f) and all counties of Nebraska in 2005 (g, h). The three counties Box Butte (Federal Information Processing Standards, FIPS 31013, June, July, and August [JJA] precipitation: 179.9 mm), Nemaha (FIPS 31127, JJA precipitation: 327.6 mm), and Chase (FIPS 31029, JJA max temperature: 30.7°C) are relatively dry, wet, and hot counties, respectively, and their locations are marked by their initials in Figure 4a,b. Error bars in the three counties (panels a–f) denote the standard error calculated from the original irrigated and rainfed MODIS pixels within each county. Error bars in all counties (panel g and h) denote the confidence interval at 95% by bootstrap (n = 1,000) from county average LST/EVI. The numbers at the bottom of panel g and h are monthly averaged differences of LST and EVI between irrigated and rainfed maize during the growing season. The numbers in blue and red colors in the second column denote irrigated and rainfed yields in 2005 (unit: bu/acre). Similar figures in other years are provided in Figure S5 for LST and Figure S6 for EVI

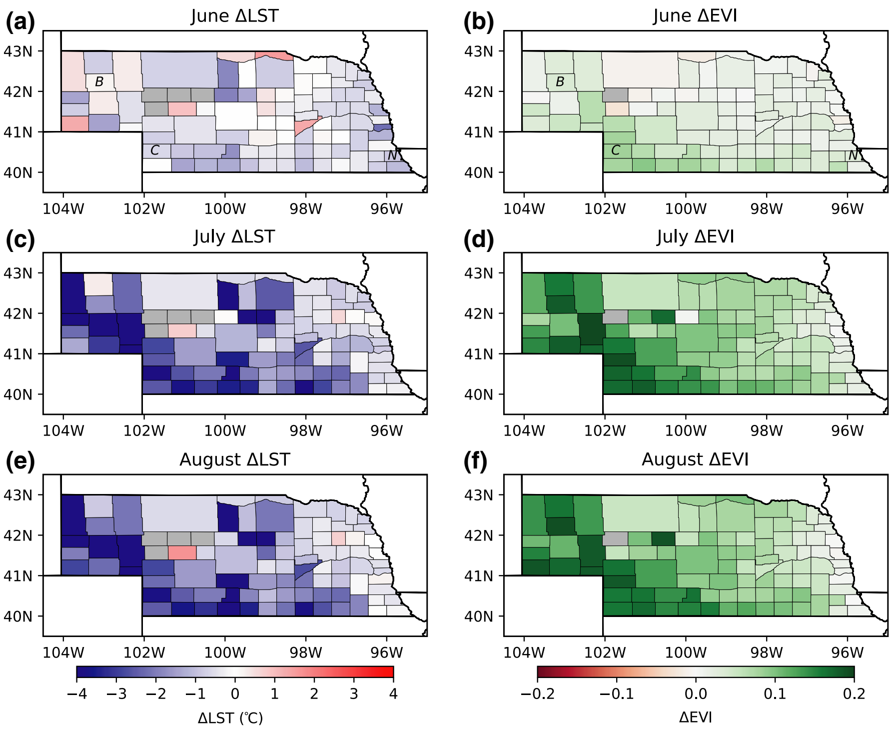

FIGURE 4 The irrigation effects on maize land surface temperature (LST; panels a, c, e) and Enhanced Vegetation Index (EVI; panels b, d, f) in June, July, and August, averaged from 2003 to 2016 in Nebraska. Grey color indicates no data. The counties with initial letters (panels a and b) mark the locations of three counties in Figure 3. A map of yield differences between irrigated and rainfed maize is shown in Figure S7

and all county average (Figure 3). Irrigated maize in three individual counties which represent different climate conditions (dry, wet, and hot, see their locations in Figure 4) had a significantly lower daytime LST, higher EVI during most of the growing season (especially in July and August), and a much higher crop yield than rainfed maize (Figure 3a–f). The lower LST found in irrigated maize marked the presence of irrigation cooling. At night, the LST differences between irrigated and rainfed maize were almost indistinguishable (data not shown), suggesting the irrigation cooling effect mainly occurs during the day. For this reason, irrigation effect at night was not included in the following analysis.

The average irrigation effects for all counties showed similar seasonal variations as the three individual counties (Figure 3g,h). The differences between irrigated and rainfed maize were initially small during the early growing season but increased progressively until the peak growing season. The largest differences in LST were observed in July (−1.63°C), followed by August (−1.19°C). The same was true for EVI with the largest differences in July (+0.10) and to a lesser extent in August (+0.09), corresponding to 20% and 18% of EVI increases relative to rainfed maize, respectively. These seasonal variations in irrigation effects reflect both the timing of irrigation and crop phenological stage. For example, irrigation application in July coincides with the peak crop growing season when the largest evapotranspiration occurs. These factors all contribute to the strongest cooling in July (Payero, Tarkalson, Irmak, Davison, & Petersen, 2009).

3.2 | Spatial and temporal variations in irrigation effect

While irrigation effects on LST and EVI (i.e., lower LST and higher EVI), which peaked in July, were observed in most counties of Nebraska, there were exceptions and noticeable spatial variations (Figure 4). First, a few counties showed the opposite irrigation effects on LST and EVI, particularly in June. The location of those exceptions differed in different months and years (Figures S8–S13). The exact reason for these exceptions is unclear, but it might be related to factors including the minimal irrigation amount in June, the accuracy of irrigated and rainfed maize classification and their crop properties extracted from remote sensing data, or some unobserved local factors at the field level. Second, there was a clear spatial transition in the irrigation effects from western to eastern Nebraska. The irrigation effects were greatest in southwest Nebraska, with an LST cooling and EVI increase in July by up to −4°C and +0.20, respectively. These effects were weakened toward northeast Nebraska as the ΔLST and ΔEVI shrank close to zero. Irrigation effect is more pronounced in western Nebraska because irrigation is required in that area to achieve high yields under a drier climatic regime. By contrast, eastern Nebraska is much wetter and irrigation is not a necessity for crop growth, meaning irrigation effects are rather small (see Sharma & Irmak, 2012a, 2012b for a description of the climatology and net irrigation requirements across Nebraska ranging from ~450

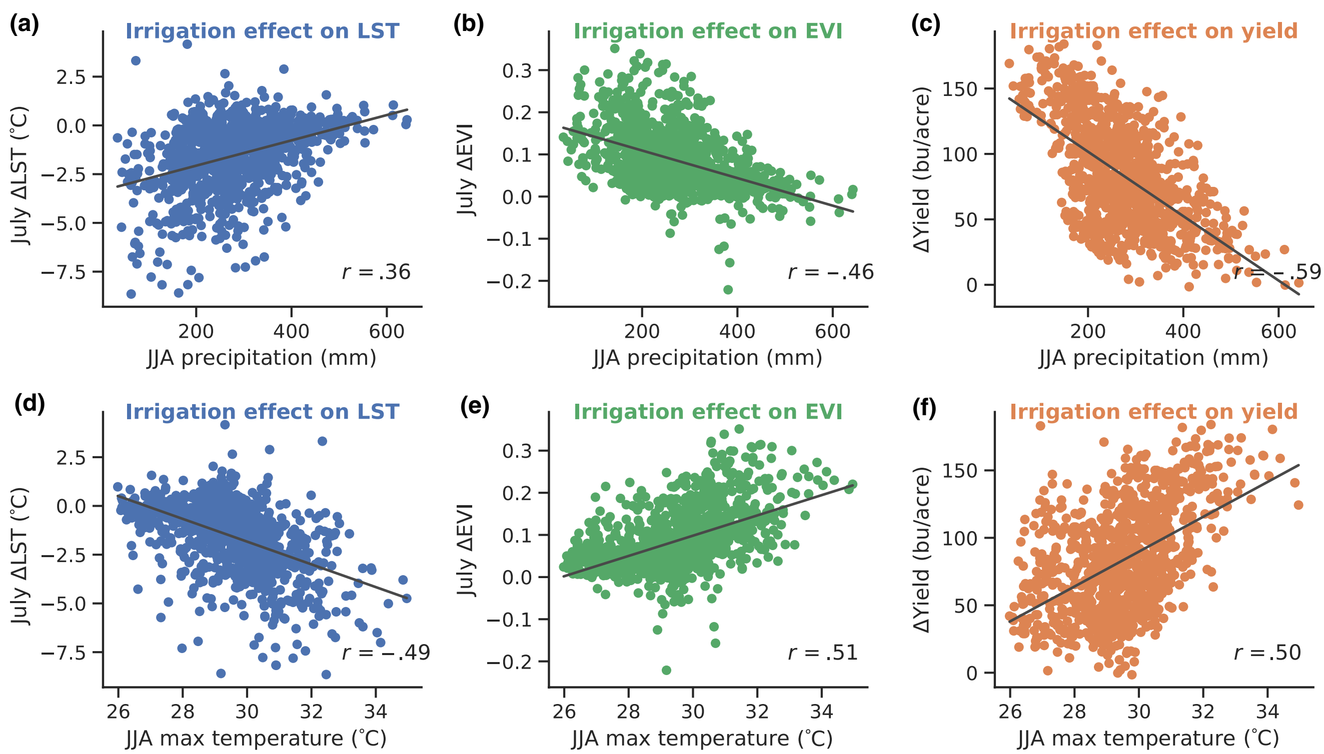

FIGURE 5 The irrigation effects on maize land surface temperature (LST; a, d), Enhanced Vegetation Index (EVI; b, e), and maize yield (c, f) in July and their relationships with summer precipitation and maximum air temperature from 2003 to 2016. Each dot in the figure represents one county-year sample. *r* is the correlation coefficient

to 50 mm/year). These spatial variations in irrigation effect were mirrored in irrigation area fractions (i.e., irrigated maize harvest area divided by the county total maize harvest area) which were high in dry western Nebraska and low in wet eastern Nebraska (Figure S14). These results highlight that the baseline climate condition is an important factor in determining irrigation effects.

Irrigation effects varied spatiotemporally with summer climate conditions (Figure 5; i.e., total precipitation and averaged maximum temperature of June, July, and August). Focus is placed on irrigation effects on LST and EVI in July due to their maximum magnitude during the growing season. Results showed that moving along the precipitation gradient from dry to wet conditions, ΔLST (*r* = .24), ΔEVI (*r* = −.30), and ΔYield (*r* = −.40) all reduced in magnitude, suggesting a weakened irrigation effect (Figure 5a–c). The weak irrigation effect under wet conditions is understandable as there is a lesser need for water supplement when precipitation is adequate. Irrigation will not benefit crop growth if it becomes excessive (Li, Guan, Schnitkey, DeLucia, & Peng, 2019; Payero et al., 2008). In contrast, irrigation effects were strengthened along the temperature gradient from cool to hot conditions, and they also exhibited stronger correlations with ΔLST (*r* = −.50), ΔEVI (*r* = .55), and ΔYield (*r* = .59), when compared to precipitation (Figure 5d,e). Therefore, irrigation effects (particularly the cooling) were expected to be greater under drier (dry counties/years) and hotter conditions (hot counties/years), primarily due to a larger amount of irrigation water applied (Thiery et al., 2017) and the different physiological responses of irrigated and rainfed crops to extreme climate conditions—rainfed crops are more likely to close their stomata than irrigated crops under hot and dry conditions. These results further demonstrate the linkage between the east–west transition in irrigation effect and climate regime.

3.3 | The contribution of cooling and water supply to irrigated maize yields

Despite irrigation effects in reducing LST and increasing EVI, the direct and most important effect of irrigation is crop yield increase. In this regard, we found that irrigated maize yield, on average, was 81% (~+80 bu/acre) higher than rainfed maize (103 bu/acre) when averaging from all counties where both irrigated and rainfed yields were available. The yield increase effect could be up to about +180 bu/acre in very dry and hot counties (Figure 5). Such yield effects from irrigation (i.e., ΔYield) can be well predicted by our statistical models (*r* = .86; Figure S4), as the predicted averaged yield increase (+79 bu/acre) was close to the observed effect (+80 bu/acre; Figure 6). We note the land evaluations also reflect these large yield differences, with center pivot irrigated cropland being assessed at $2,700/acre and rainfed being evaluated at $700/acre in 2018 for Northwest Nebraska (Jansen & Stokes, 2018).

Following the quantification method in Section 2.2.2, we found that 16% of the irrigation yield increase in Nebraska was due to irrigation cooling, whereas 84% of yield increase was due to water supply (Figure 6). It should be noted that the estimated water supply contribution could also contain effects of other agronomic factors related to water (see Section 4). Although the relative contributions of these two varied in different years, the irrigation yield effect was still dominated by water supply while contribution of cooling was relatively stable. In particular, irrigation effect was largest in the extreme drought year of 2012. Rainfed maize yield in Nebraska in 2012 decreased by 61% compared to the previous year (46 bu/acre vs. 118 bu/acre), whereas irrigated yield was essentially not affected by drought and remained high (186 bu/acre vs. 179 bu/acre). This suggests that irrigation can effectively buffer the negative impact of extreme weather on crop yield, as noted by previous studies (Thiery et al., 2017; Troy et al., 2015). These

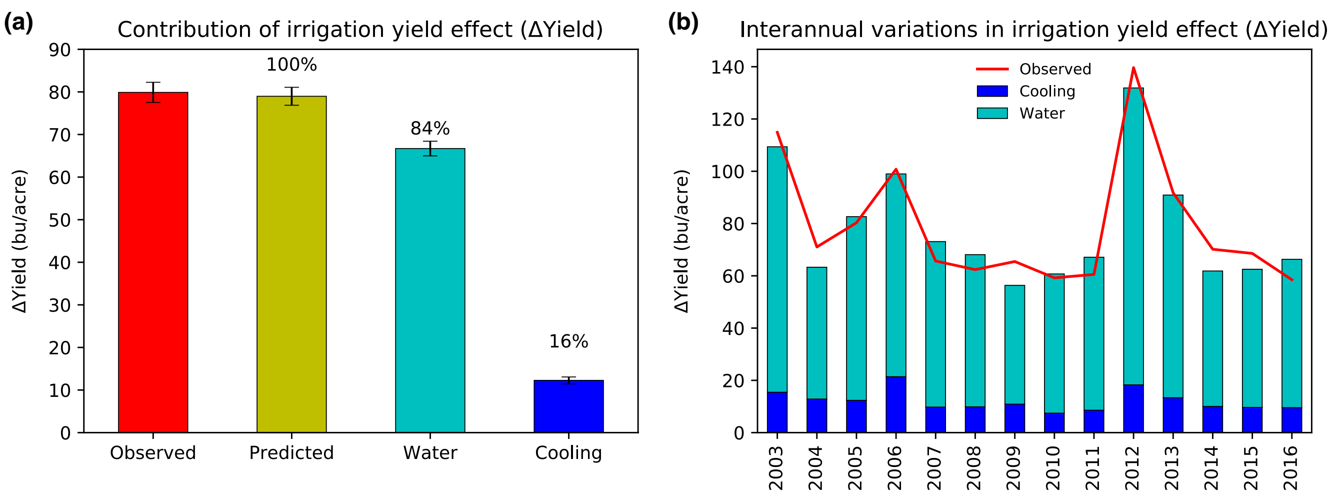

FIGURE 6 (a) The contribution of cooling and water supply to irrigation yield increase and (b) their interannual variations from 2003 to 2016. Note that 'water' stands for 'water supply and other factors'. The irrigation yield effect is expressed as the yield differences between irrigated and rainfed maize. The averages of observed and predicted yield differences between rainfed and irrigated maize are 79.0 and 79.9 bu/acre, respectively. The irrigation effect shown in panel (a) is averaged from all counties during the study period

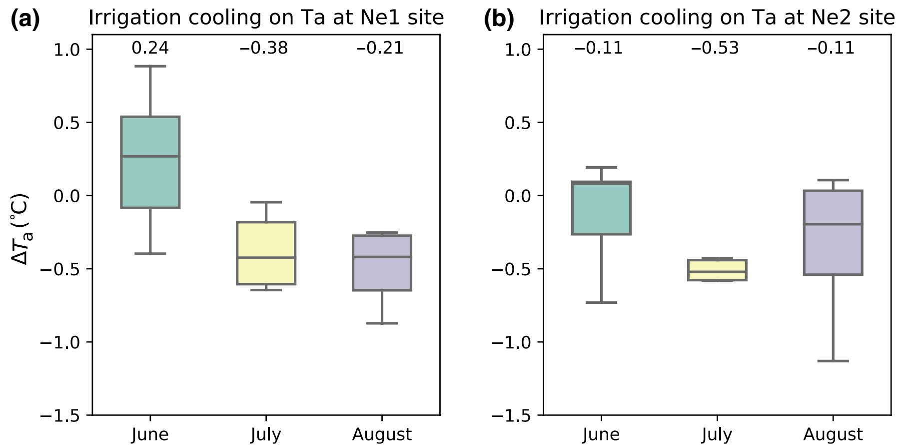

FIGURE 7 Irrigation cooling effect on daytime air temperature in maize flux tower sites in Nebraska (a, Ne1 site; b, Ne2 site). The cooling effect is estimated as the differences in air temperature between irrigated and rainfed sites in odd years from 2003 to 2013 when maize is planted. The numbers on top indicate the averaged air temperature differences between irrigated and rainfed maize sites

results reveal that irrigation cooling has a non-negligible contribution to crop yield increase from irrigation, besides water supply.

3.4 | Irrigation cooling on air temperature from flux tower sites

The irrigation cooling identified from satellite remote sensing is based on LST. LST is physically different from air temperature (Ta) although these two are correlated (Jin & Dickinson, 2010). It is unclear whether irrigation induced cooling can be observed with air temperature. To investigate this matter, we analyzed air temperature measurements from two paired flux tower sites of irrigated and rainfed maize in Nebraska. Results in Figure 7 showed that irrigation cooling on air temperature (denoted as ΔTa) can be clearly seen from two pairs of site comparisons (Ne1–Ne3 and Ne2–Ne3). The effect on air temperature (ΔTa) exhibited seasonal patterns similar to that of ΔLST at both sites, with the strongest cooling in July (−0.38°C for Ne1 and −0.53°C for Ne2), weak or no cooling effect in June and moderate cooling effect in August (the absence of cooling in June is probably a result of minima irrigation within the month). However, the magnitude of cooling on air temperature (−0.38 to −0.56°C) was smaller than LST in the Saunders county where these sites are located (<−1°C in July, FIPS 31155). This difference could be caused by their different spatial scales and factors, as summarized in Li et al. (2015): (a) the inherent differences between air temperature and LST; (b) retrieval of LST under the clear-sky conditions; and (c) different temporal samplings (13:30 for LST while daytime averages for air temperature).

4 | DISCUSSION

4.1 | Interactions among processes involved in irrigation effects

The irrigation cooling effect observed on LST reflects contributions from different factors, including increased soil moisture and enhanced vegetation growth (Figure 8). Irrigation water directly increases soil moisture and strengthens evaporative cooling. This is further intensified as irrigated crops grow significantly better than rainfed crops with more leaf area and biomass, which increase plant transpiration and thus exert an even stronger cooling. Such a cooling from transpiration partially explains why the largest irrigation cooling period corresponded to the peak growing season (i.e., July in Figure 3). In fact, these processes of moisture and evapotranspiration are intertwined in a way where irrigation cooling (through evaporation) promotes crop growth, and the more vigorously grown crops, in turn, enhance the cooling (through transpiration). Although our statistical model separated cooling and water supply in the irrigation yield effect, what we observed in reality will always be the combined effect of these processes. For process-based crop models, it is still challenging to capture all these interactive processes, as it requires crop models to include both canopy energy balance and biochemical photosynthesis components to simulate the LST cooling (for cropland in peak growing season, it is mainly canopy temperature cooling) and its effect on crop growth, which are still absent in many agronomy crop models (Peng et al., 2018). To simulate the cooling effects on air temperature and crop growth, crop models have to be bidirectionally coupled with an atmosphere model (Harding, Twine, & Lu, 2015; Lu, Jin, & Kueppers, 2015).

4.2 | Irrigation cooling effect at different spatial scales

The cooling on LST showed in our study is an indication of how vegetation actively regulates their thermal environment at the plant scale. The cooling observed on air temperature from flux tower comparisons further confirms that irrigation changes the microclimate surrounding irrigated crops. However, it should be clarified that irrigation cooling found in our study at small scales is not the same as the regional cooling reported in studies that focus on irrigation impact on local and regional climate through land–atmosphere interaction (Kueppers et al., 2007; Lobell et al., 2008; Lu, Harding, & Kueppers, 2017; Sacks et al., 2008; Santanello, Peters-Lidard, & Kumar, 2011; Thiery et al., 2017; Figure 8). The cooling effect in our study is quantified by a spatial comparison approach, which assumes that irrigated and rainfed crops are located in the same background climate conditions, and their differences reflect the irrigation effect. This assumption means

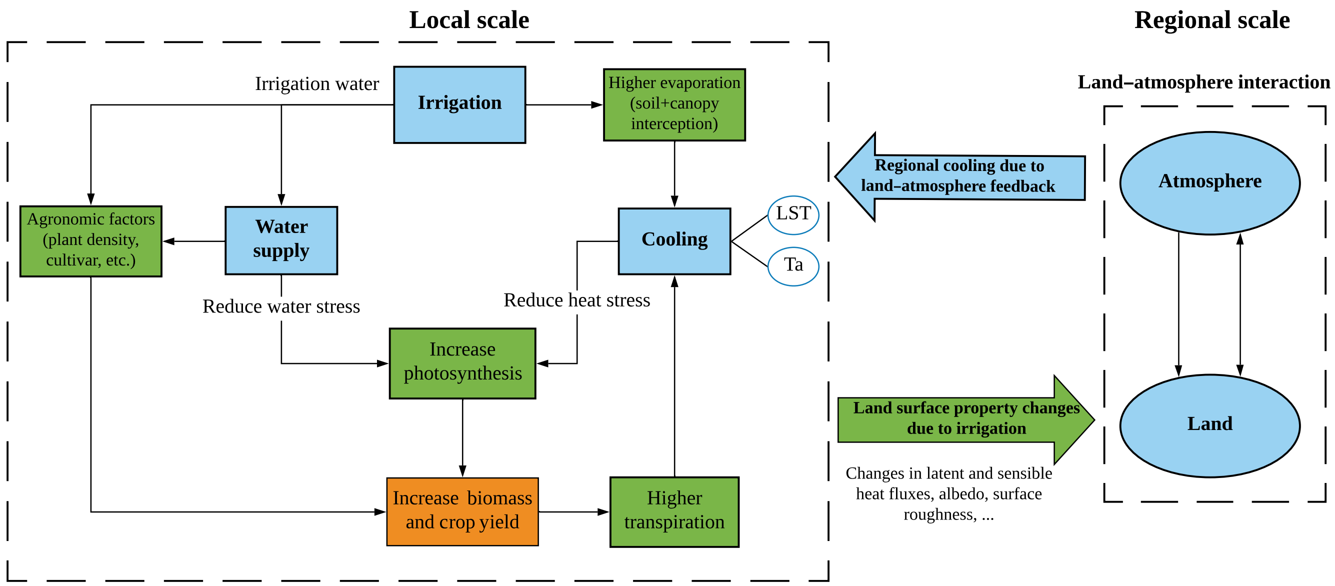

FIGURE 8 Summary of the irrigation effects on crop yield and their interactions with climate. LST, land surface temperature; Ta, air temperature

irrigation would not trigger significant changes in the background climate state, thereby excluding the atmosphere feedback that may cause nonlocal impacts in remote regions (Winckler, Lejeune, Reick, & Pongratz, 2019). This is the key difference regarding the irrigation cooling effect between small- and large-scale studies. In fact, the irrigation cooling effect on climate could go beyond the scope of micro and local climate and affect remote precipitation pattern if irrigation area becomes sufficiently large, which seems to be already the case in many intensive agricultural areas (e.g., US Corn Belt; DeAngelis et al., 2010; Huber et al., 2014; Mueller et al., 2015; Szilagyi, 2018). As a result, irrigation can become a climate forcing that not only drives regional climate change (Kueppers et al., 2007; Mahmood et al., 2006; Mueller et al., 2015) but also could have global climate consequences (Sacks et al., 2008). It also suggests that changes in agricultural practice could interact with climate and then influence crop growth and yields (Butler, Mueller, & Huybers, 2018).

4.3 | Uncertainties in separating the contribution of irrigation effect

The separation of cooling and water supply relies on satellite remote sensing data and statistical model, as a result, the quantification results would inherit uncertainties from the data and method used. First, there are uncertainties in the thematic classification of maize pixels from CDL and the 2005 irrigation facility map, which were used to identify the location of irrigated and rainfed maize fields. Our assumption that the field-level irrigation map made for 2005, as being valid for other years, could result in some misclassification of irrigated and rainfed fields—as some irrigated lands may have been retired, while other areas may have experienced irrigation expansion post 2005. Second, irrigated and rainfed crop fields on the ground may not be fully distinguished by the coarser spatial resolution of MODIS. The mixed pixel may confound the extracted crop properties of irrigated and rainfed maize, which is more of an issue for LST (1 km) than EVI (250 m). To mitigate this issue, we only selected MODIS-scale pixels with the majority of its area composed of 30 m irrigated or rainfed maize for analysis. All these factors add to uncertainties in the extracted signals from satellite remote sensing data for irrigated and rainfed maize. However, irrigation effects identified on LST and EVI are unlikely to be significantly altered by these uncertainties, as validation showed reasonable performance (Figures S1–S3) and the extracted signals, such as LST cooling and EVI increase, agree with our expectations.

Since irrigation benefits on crop yield are separated into cooling and water supply with statistical models, the reliance on statistical models means that the estimated specific contributions will likely be different with different model configurations, but the relative importance of cooling and water supply is robust to model choices. While the cooling effect on yield is quantified as the yield change due to temperature difference imposed by irrigation, the water supply effect is quantified as the yield difference between irrigated and rainfed crops if they had the same temperature. Our results showed that the water supply effect, unsurprisingly, dominated the yield gain from irrigation. It should be noted that the water supply effect might be overestimated with this method because the yield difference between irrigated and rainfed crops under the same temperature condition is attributed solely to water supply. In fact, irrigated and rainfed crops could be different in other agronomic aspects (though these are indirectly related to water supply) such as crop variety (Tack et al., 2017) and management practices (planting date, density, and nitrogen application; Barr, Mason, Novacek, Wortmann, & Rees, 2013; Tenorio, 2019) which may also contribute to yield differences.

Among these agronomic differences, planting density needs to be taken into account when directly comparing irrigated and rainfed yields, as irrigated crops usually have a higher planting density

(Barr et al., 2013; Klein & Lyon, 2003). The 2012 USDA farmer survey reported that the average plant population at harvest was 29,000 plants/acre for irrigated maize and 21,850 plants/acre for rainfed maize in Nebraska (Barr et al., 2013). To investigate the effect of different plant densities on irrigation yield effect, we applied a correction factor to adjust raw irrigated yield to an equivalent yield with the same plant density as rainfed maize (see Supporting Information for more details). Due to a lack of reliable data, we used irrigated and rainfed maize plant density from the 2012 USDA survey for this analysis. The correction factor was estimated based on a linear relationship between plant density and irrigated yield in Nebraska (Barr et al., 2013). Results indicated that the higher plant density of irrigated maize relative to rainfed maize in Nebraska, on average, resulted in a yield increase of 12.28 bu/acre. The plant density effect was estimated to be 15% of ΔYield and it is included as a part of the 'water supply' effect (84%; Figure 6). However, the plant density effect should be interpreted with caution because the data used for estimations are subject to uncertainties and several assumptions were made (see detailed calculation in Supporting Information). In fact, the plant density differences between irrigated and rainfed maize are not independent of irrigation water (Holt & Timmons, 1968). The higher plant density of irrigated maize could be understood as a consequence of irrigation water supply for both biophysical and economic considerations (Karlen & Camp, 1985). In essence, additional water allows plants to grow densely while meeting their water demand, and increased yield of high plant density is needed to offset costs associated with irrigation to ensure profitability. Therefore, the water supply effect, identified in our analysis, practically includes contributions from both water supply and other related factors.

Some important factors of irrigation are not taken into account in our analysis due to lack of data, such as the amount, timing, and duration of irrigation. In our study, irrigation is considered as a binary situation and we assumed that producers would make sensible decisions of their specific irrigation strategies to maximize crop yields while being cost-effective. However, the binary irrigation treatment is highly simplified and the actual irrigation practice and the resulting changes are far more complicated than this. Although simplification is necessary for large-scale study, the effects of these granular factors of irrigation practice require further investigation.

Our study provides observational evidence of how irrigation changes crop growth and crop properties with satellite remote sensing data (LST and EVI) and disentangle two key processes by which irrigation increases crop yield: irrigation cooling and water supply. While results showed that water supply dominates the irrigation yield increase as it reduces water stress, we also found that irrigation cooling has a non-negligible contribution to crop yield as it reduces heat stress, and the latter was not well recognized in previous studies. The spatiotemporal variations in the irrigation effect found in our results highlight the strong influence of background climate conditions. With projected shifting precipitation patterns and more frequent droughts and heatwaves in the future (Huang et al., 2017; Wuebbles et al., 2017), a large expansion of irrigation would be required to sustain current maize yield trends in the United States (DeLucia et al., 2019; McDonald & Girvetz, 2013). Within this context, irrigation effects are expected to be intensified, leading to a greater synergistic effect of crop yield increase and cooling benefit. However, these co-benefits are likely to be accompanied by other water and environment-related issues. Therefore, interactions between irrigation effect and climate through cooling and water supply are key linkages to understand the consequences of future irrigation development on crop production and its potential feedback to regional climate, and they will provide the scientific basis to guide sustainable irrigation practice under future climate change.

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AUTHOR CONTRIBUTION

Y.L. and K.G. conceived and designed the study; Y.L. performed the data analysis; Y.L. and K.G. analyzed the results; Y.L. and K.G. wrote the manuscript with contributions from B.P., T.F., B.W., and M.P.; T.F. and B.W. provided the 2005 Nebraska irrigation map data.

DATA AVAILABILITY STATEMENT

The processed data and code of this study are freely available at Figshare (doi: https://doi.org/10.6084/m9.figshare.10330688).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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