Assessing the contribution of cooling and water supply to yield benefits due to irrigation

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Abstract:

Irrigation is essential to sustain 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 crop. These irrigation effects vary along the spatial and temporal gradients of precipitation and temperature, with greater effect in dry and hot conditions, and decline towards 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 reveals the non-negligible contribution of irrigation cooling in the yield increase due to irrigation, and such an effect may become more important in the future with continued warming and more frequent droughts.

Keywords: irrigation, cooling, water, maize yield, LST

1. Introduction

Irrigation is essential to sustain crop production, especially in arid and semi-arid regions where crop growth is limited by water (Elliott et al., 2014). Crops benefit from irrigation in several aspects. With irrigation, crops are generally more productive than those under rainfed conditions, with increased leaf area/biomass, evapotranspiration, and higher water use efficiency (Payero, Tarkalson, Irmak, Davison, & Petersen, 2008; Grassini, Yang, & Cassman, 2009; Oweis, Zhang, & Pala, 2000), which collectively translate into higher crop yield. Further, irrigation essentially decouples crop yield from climate, buffering yield variability due to climate fluctuation (Troy, Kipgen, & Pal, 2015; Li et al., 2019; Shaw, Mehta, & Riha, 2014). Irrigation also improves crop resilience by partially offsetting the negative impacts from water stress under extreme drought and warming conditions (Troy, Kipgen, & Pal, 2015; Tack, Barkley, & Hendricks, 2017).

These various benefits of irrigation are underpinned by 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 crops' water demands. Such water supply effect is not limited to dry 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, Yang, & Cassman, 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 cooling effect (Siebert, Webber, Zhao, & Ewert, 2017; Lobell, Bonfils, Kueppers, & Snyder, 2008; Szilagyi, 2018). Several empirical and modeling studies have found significant cooling over intensively irrigated areas such as the West (Kueppers, Snyder, & Sloan, 2007) and Midwest United States (MAHMOOD et al., 2006; Huber, Mechem, & Brunsell, 2014), the North China (Wu, Feng, & Miao, 2018) and Northeast China (Zhu, Liang, & Pan, 2012), and India (Douglas, Beltrán-Przekurat, Niyogi, Pielke, & Vörösmarty, 2009). The cooling effect is particularly strong in reducing maximum temperature (Bonfils & Lobell, 2007) and becomes more pronounced during hot days (Thiery et al., 2017). Since crop yield is highly sensitive to high temperature and vapor pressure deficit (VPD), this cooling effect benefits crops by reducing heat stress (Siebert, Webber, Zhao, & Ewert, 2017; Siebert, Ewert, Rezaei, Kage, & Graß, 2014) and evaporative demand (Nocco, Smail, & Kucharik, 2019), and mitigating the impacts of extreme heat (Vogel et al., 2019). In particular, cooling can shift the high temperature thresholds of crops beyond which yield declines so that crops become more tolerant to extreme weather (Troy, Kipgen, & Pal, 2015; Carter, Melkonian, Riha, & Shaw, 2016; Schlenker & Roberts, 2009; Lobell et al., 2013).

Irrigation effects on crops have been extensively studied in previous studies (Payero, Tarkalson, Irmak, Davison, & Petersen, 2008; Butler, Mueller, & Huybers, 2018; Tack, Barkley, & Hendricks, 2017; Troy, Kipgen, & Pal, 2015; Carter, Melkonian, Riha, & Shaw, 2016; Oweis, Zhang, & Pala, 2000), however, much attention has been paid to the water supply aspect of irrigation (Szilagyi, 2018), while the cooling effect of irrigation on crop yield has not been in the focus. Although it is well-known that water supply and cooling are two key mechanisms responsible for yield gains of irrigation (Walker, 1989), their effects on crop yield benefits have not been separately quantified.

In this study, we aim to quantify the irrigation effects from multiple observation data and to disentangle the contribution of water supply and irrigation cooling on crop yield benefits. We first analyzed the irrigation effects on crop growth and their spatial and temporal variations with satellite remote sensing and yield observation data. Irrigation effects (including cooling and biomass/yield changes) were quantified by comparing land surface temperature (LST), enhanced vegetation index (EVI), and yields between irrigated and rainfed maize in Nebraska. Next we proposed a statistical method to quantify the separate contribution of water supply and cooling in yield benefits of irrigation. Our analysis focused on maize for the state of Nebraska, USA. Nebraska was selected as the study region because it is a major maize-producing state in the United States with an extensive irrigation/precipitation gradient (Szilagyi, 2018). During the study period (2003-2016), irrigated maize accounted for 56% of the total maize harvest area and 65% of maize production in Nebraska.

2. Materials and methods

2.1 Data

(1) MODIS remote sensing data

We used 8-day LST data (MYD11A2) at 1km spatial resolution and 16-day Enhanced Vegetation Index (EVI, MYD13Q1) data at 250m 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 13:30/1:30. The LST data were used to quantify the irrigation cooling effect.

(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 30m 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 was used in conjunction with the 30m maize map extracted from Crop Data Layer (CDL) from 2003 to 2016 to determine the locations of irrigated and rainfed maize fields in Nebraska.

(3) Statistical crop yield data

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

(4) Gridded and flux tower climate data

The gridded daily PRISM climate data from 2003 to 2016 include maximum and minimum air temperature and precipitation (ftp://prism.oregonstate.edu/). The data originally had a spatial resolution of 4km and were averaged to county-level to reflect climate condition of each county. To verify the irrigation cooling at the field level, we used daytime air temperature measurements ("TA_F_MDS" variable) from 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 but maize and soybean are rotated (maize in odd years during 2001–2009 and all years from 2010 to 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 signal, the paired differences between irrigated and rainfed sites such as Ne1-Ne3 and Ne2-Ne3 are indicative of the irrigation effect on air temperature.

2.2 Method

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

In this study, irrigation effect is quantified as the county-level differences in crop properties (i.e., yield, LST, and EVI) between irrigated and rainfed maize. While irrigated and rainfed maize yields in each county are readily available from NASS, their LST and EVI in each county have to be extracted by the procedure implemented in Google Earth Engine described below (Figure S1).

The irrigation map was first overlaid with CDL data in 2005 to extract irrigated and rainfed maize pixels at 30m resolution. These 30m pixels were then spatially aggregated to create irrigated and rainfed maize masks at MODIS resolutions with the majority method (1km for LST and 250 m for EVI 250m). The resulting masks were combined with MODIS data to extract LST/EVI of irrigated and rainfed maize so that their differences can be computed in each county. This only gives LST and EVI of irrigated and rainfed maize and their differences in 2005, because the irrigation map is developed only for for 2005. In order to make this method work for other years, we assumed that the irrigation map produced for 2005 also applies to other years. To test this assumption, we compared irrigated and rainfed maize area in other years derived under this assumption with statistics from NASS. If the assumption was not accurate, the derived maize harvest area would show a large bias against NASS statistics. We found high correlations between these two from our our validation results, which supported the validity of this assumption (r=0.99 and r=0.94 for irrigated and rainfed maize area from 2003 to 2016 respectively, see Figures **??** and **??**).

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

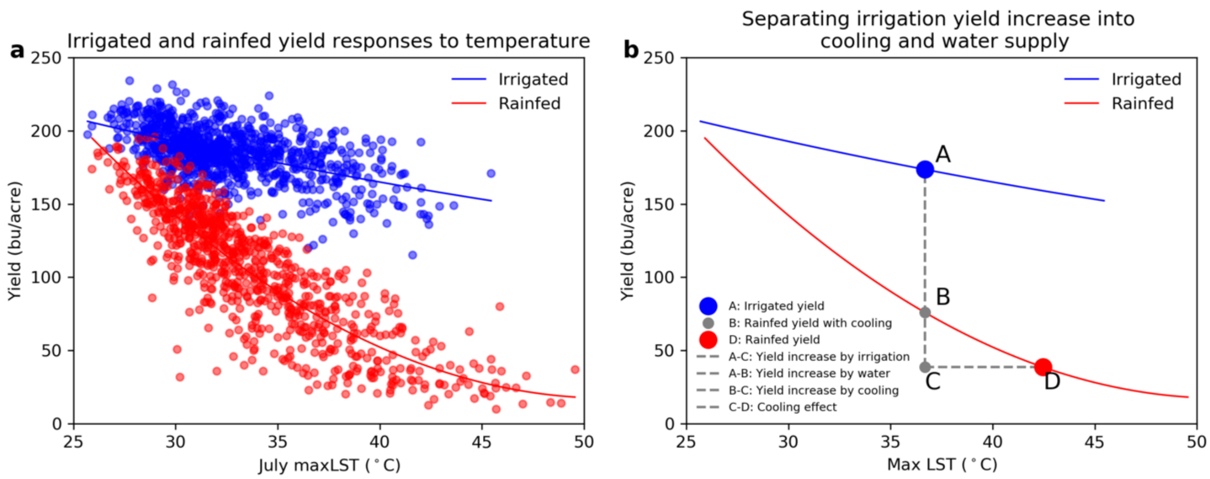

Figure 1: (a) Yield responses of irrigated and rainfed maize to July maximum LST. (b) Schematic diagram of separating the effects of water supply and cooling in the irrigation maize yield increase in Nebraska.

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 1a). Suppose a county grows both irrigated and rainfed maize in Figure 1b, 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 between them 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 discussion).

The above idea can be implemented rigorously using statistical models. The statistical model was constructed using monthly LST and precipitation from June to August as independent variables to predict county yield. The model configuration is shown below:

$$yield = a \cdot year + \sum_{m=June}^{Aug} \left(b_m \cdot LST_m + c_m \cdot LST_m^2 + d_m \cdot P_m + e_m \cdot P_m^2\right) + c_0 \text{ Eq.1}$$

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 increase yield trends due to improvements in management and technology. By training the model with yield data of rainfed and irrigated maize respectively, we would have two models, one for rainfed maize (Eq. 2) and another one for irrigated maize (Eq. 3):

Rainfed maize model: $Yield_{rain} = f_{rain}(LST_{rain}, P)$ Eq. 2

Irrigated maize model: $Yield_{irr} = f_{irr}(LST_{irr}, P)$ Eq. 3

where f_{rain} and f_{irr} are the fitted functions (i.e., the right-hand side of Eq. 1) for rainfed and irrigated maize, respectively. The water supply effect embeds the function f_{irr} intrinsically which gives rise to a higher yield. These statistical models serve as a tool to emulate temperature response curves in Figure 1b mathematically. The models after training can explain about 85% and 46% of spatiotemporal yield variations of rainfed and irrigated maize from 2003 to 2016, respectively (Figure S13). The relatively lower explanation power of irrigation model was expected as it reflected the fact that irrigated crop yield is more stable and less sensitive to climate variability (Troy, Kipgen, & Pal, 2015; Li et al., 2019; Shaw, Mehta, & Riha, 2014). The predicted yield difference (irrigated versus rainfed) showed high correlation with their actual yield differences (r=0.86). This good model performance enabled us to separate the irrigation effect on crop yield into cooling and water supply.

The cooling effect on yield, $\Delta Yield_{cooling}$, is defined as the hypothetical yield increase in rainfed maize if the same cooling as irrigated maize was applied. $\Delta Yield_{cooling}$ can be calculated by Eq.4 as the yield predicted by rainfed maize model with irrigated LST minus the yield predicted by rainfed model with rainfed LST. Similarly, the water supply effect on yield, $\Delta Yield_{water}$, is defined as the yield increase in rainfed maize if additional water was added as irrigated maize. It is can be calculated by Eq.5 as the yield predicted by irrigated maize model with irrigated LST minus the yield predicted by rainfed maize model with the same irrigated LST.

$$\Delta Yield_{cooling} = f_{rain}(LST_{irr}, P) - f_{rain}(LST_{rain}, P) \quad \text{Eq.4}$$

$$\Delta Yield_{water} = f_{irr}(LST_{irr}, P) - f_{rain}(LST_{irr}, P) \quad \text{Eq.5}$$

3. Results

3.1 Irrigation effects on LST, EVI, and maize yield

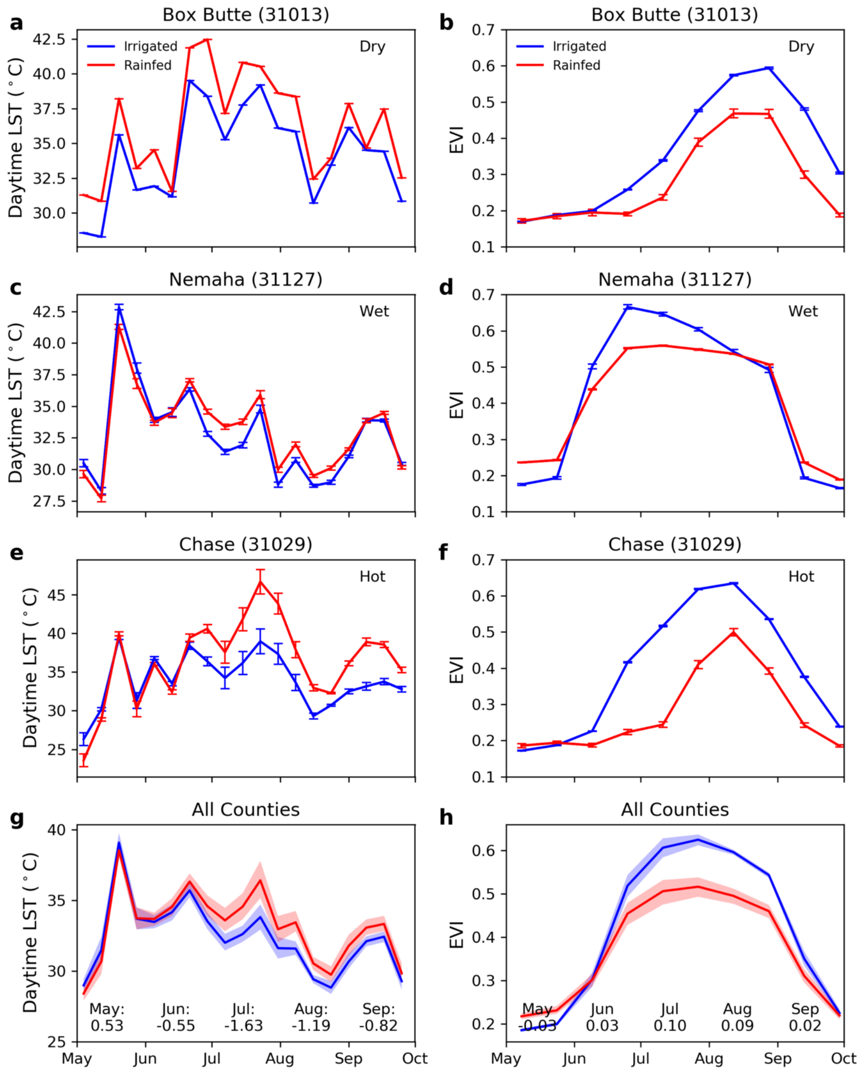

Figure 2: Irrigation effects on LST and EVI of maize in Nebraska in 2005 in three selected counties (a to f) and all counties (g, h). Box Butte (FIPS 31013, JJA precipitation: 179.9 mm), Nemaha (FIPS 31127, JJA precipitation: 327.6 mm), and Chase (FIPS 31029, JJA max temperature: 30.7 °C) are relatively dry, wet, and hot counties, respectively, during the study period. Error bars in the three counties (panels a to f) denote the standard error calculated from the original MODIS pixel within each county. Error bars in all counties (panel g and h) denote the confidence interval at 95% by bootstrap (n=1,000) from the county average LST/EVI. The numbers at the bottom of panel g and h are the monthly averaged differences of LST and EVI between irrigated and rainfed maize.

The irrigation effect on the crop was manifested as the differences between rainfed and irrigated maize, which can be seen in individual counties and all county average (Figure 2). In three individual counties selected to cover different climate conditions (dry, wet, and hot), irrigated crops had a significantly lower daytime LST and higher EVI than rainfed crops during most of the growing season, especially in July and August (Figure 2a-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 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 presented earlier (Figure 2g,h). The differences between irrigated and rainfed maize were initially small at 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 less extent in August (0.09).

3.2 Spatial and temporal variations in irrigation effect

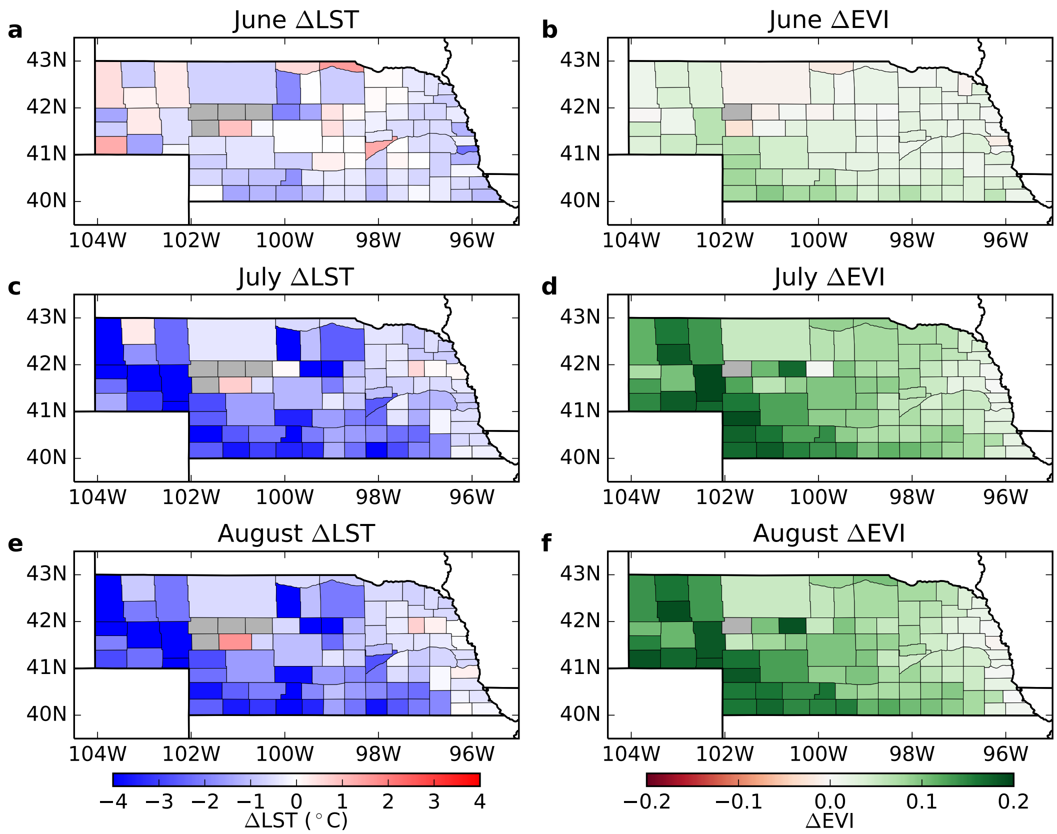

Figure 3: The irrigation effects on LST and EVI of maize in June, July and August, averaged from 2003 to 2016 in Nebraska. Grey color means no data. A map of yield differences between irrigated and rainfed maize is shown in Figure S6.

While irrigation effects on LST and EVI (i.e., lower LST and higher EVI), which peaked in July, were found in the majority of Nebraska counties, there were exceptions and markedly spatial variations (Figure 3). First, a few counties showed the opposite irrigation effects on LST and EVI, particularly in June and to a less extent in other months. The location of those exceptions differed in different months and years (Figures S7 to S12). The exact reason for these exceptions is not clear, but might be related to the minimal irrigation in June, the accuracy of irrigation map and remote sensing data, or some unobserved local factors at the field level.

Second, there was a clear spatial transition in the irrigation effects from west to east Nebraska. The irrigation effects were greatest in southwest Nebraska, with an LST cooling and EVI increase in July by up to -4°C and +0.2°C, respectively. These effects were weakened towards northeast Nebraska as the ΔLST and ΔEVI shrank to 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, so that irrigation is not a necessity for crop growth, therefore, irrigation effects are rather small. See (Sharma & Irmak, 2012; Sharma & Irmak, 2012) for a description of the climatology and net irrigation requirements across Nebraska ranging from ˜450 mm/yr to 50 mm/yr. These results reveal that the baseline climate condition is an important factor in determining irrigation effects.

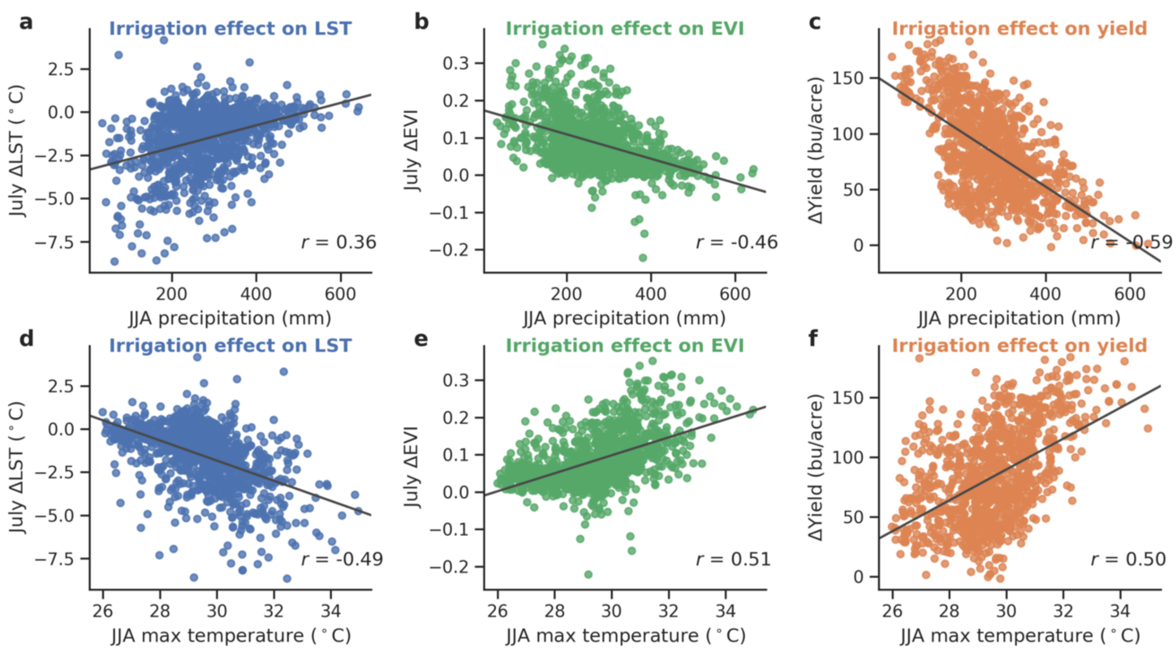

Figure 4: The irrigation effects on July LST (a,d), July EVI (b,e), and maize yield (c,f) and their relationships with summer precipitation and max air temperature across space and time. *r* is the correlation coefficient. This figure includes data from 2003 to 2016.

Figure 4 shows how irrigation effects varied spatiotemporally with summer climate conditions (i.e., total precipitation and averaged max temperature of June, July, and August). Here we focus on irrigation effects on LST and EVI in July as they had the largest magnitude in the growing season. Results showed that from dry to wet conditions along the precipitation gradient, ΔLST (r=0.24), ΔEVI (r=-0.30) and $\Delta Yield$ (r=-

0.40) between irrigated and rainfed maize all reduced, suggesting a weakened irrigation effect (Figure 4a-c). The weak irrigation effect under wet conditions is understandable, because there is much less need to supply additional water when precipitation is adequate. Irrigation will not benefit crop growth if it becomes excessive (Payero, Tarkalson, Irmak, Davison, & Petersen, 2008; Li, Guan, Schnitkey, DeLucia, & Peng, 2019). In contrast, irrigation effects were strengthened from cool to hot conditions along the temperature gradient, and ΔLST (r=-0.50), ΔEVI (r=0.55) and $\Delta Yield$ (r=0.59) all had higher correlations with temperature than precipitation (Figure 4d-e). Therefore, irrigation effects such as irrigation cooling were expected to be greater under drier or hotter conditions, including either dry and hot counties (spatially) or dry and hot years (temporally). These results also explain how the east-west transition in irrigation effect of Nebraska is connected to climate regime.

3.3 Quantify the contribution of cooling and water supply

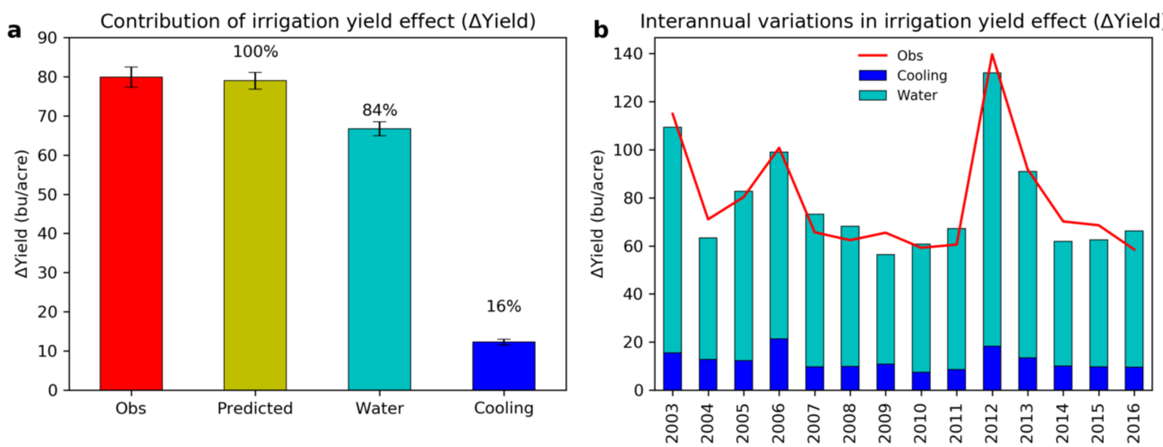

Figure 5: The contribution of cooling and water supply to irrigation yield increase (a) and their interannual variations from 2003 to 2016 (b). The irrigation yield effect is expressed as the yield differences between irrigated and rainfed maize. The averages of observed and predicted yield differences 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.

Despite the irrigation effects that reduce LST and increase EVI identified from satellite remote sensing data, the direct and most important effect of irrigation is to increase crop yield. In this regard, irrigation increased maize yield in Nebraska by ˜80 bu/acre (+81%) relative to rainfed maize (103 bu/acre) when averaging from all counties where both irrigated and rainfed yields were available. The yield effect could be up to ˜+180 bu/acre in very dry and hot counties (Figure 4). Such yield effect of irrigation (i.e., delta Yield) can be well predicted by our statistical models (r=0.86, Figure S13), and the averaged predicted yield gain (79 bu/acre) was close to the observed effect (80 bu/acre, Figure 5). We note the land evaluations also reflect these large yield differences, with center pivot irrigated crop being assessed at $2700/acre and rainfed being evaluated at $700/acre in 2018 for Northwest Nebraska (Jim Jansen, 2018).

Following the quantification method in Section , we found that 16% of irrigation yield increase in Nebraska was due to irrigation cooling, whereas 84% of yield increase was due to water supply (Figure 5). Although the relative contributions of these two varied in different years, the irrigation yield effect was still dominated by water supply while cooling contribution was relatively stable. In particular, irrigation effect was the largest in the extreme drought year of 2012. This suggests that irrigation can effectively buffer the negative impact of extreme weather on crop yield, as suggested by previous studies (Troy, Kipgen, & Pal, 2015; Thiery et al., 2017). These results reveal that irrigation cooling has as a non-negligible contribution to crop yield gain of irrigation besides water supply.

4. Discussion

4.1 Irrigation cooling on air temperature from flux tower sites

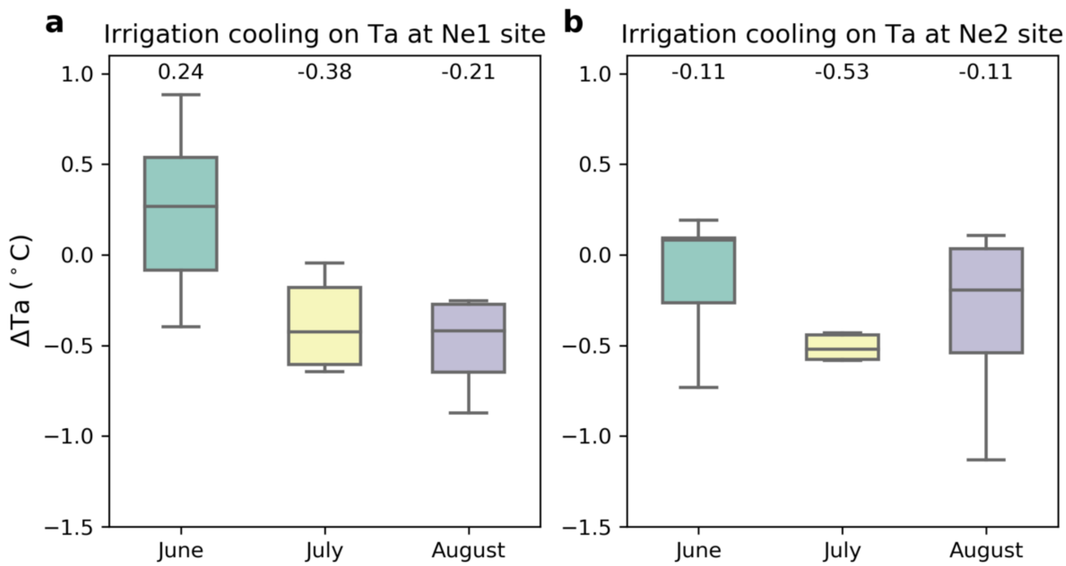

Figure 6: Irrigation cooling effect on daytime air temperature by comparing irrigated and rainfed maize flux tower sites in odd years from 2003 to 2013.

The irrigation cooling identified from satellite remote sensing is based on LST, which is physically different from air temperature (Ta) although these two are correlated (Jin & Dickinson, 2010). It is unclear whether irrigation 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 showed that irrigation cooling on air temperature (denoted as ΔTa) can be clearly seen from two pairs of site comparison (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 because irrigation is minimal in June in Mead site). However, the magnitude of cooling on air temperature was smaller than LST (-1.63 °C in July). This difference could be caused by factors mentioned in (Li et al., 2015): (1) the inherent differences between air temperature and LST, (2) the clear-sky only retrieval of LST, and (3) different temporal samplings (1:30PM for LST while daytime averages for air temperature).

4.2 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 7). On one hand, irrigation water directly increases soil moisture and strengthens evaporative cooling. On the other hand, irrigated crops grow significantly better with more leaf area and biomass, which increase plant transpiration and thus exert an even stronger cooling. Such cooling from transpiration partially explains why the largest irrigation cooling corresponded to the peak growing season (i.e., July in Figure 2). 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 from 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 bi-directionally coupled with an atmosphere model (Lu, Jin, & Kueppers, 2015; Harding, Twine, & Lu, 2015).

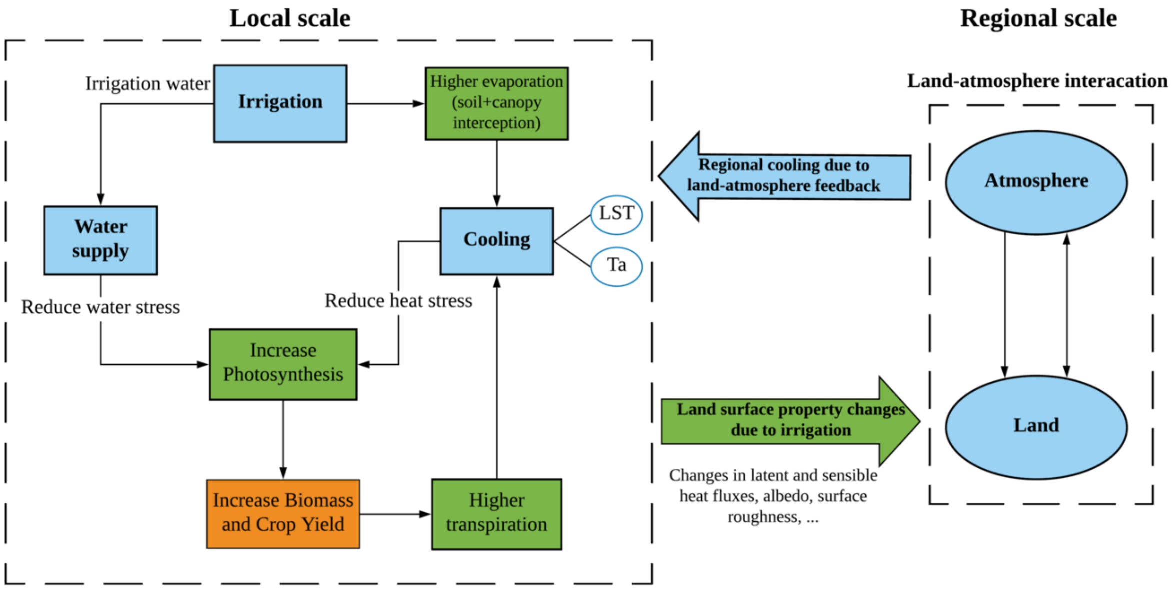

Figure 7: Summary of the irrigation effects on crop yield

4.3 Irrigation cooling effect at different scales

The cooling on LST shown in our study is also an indication of how vegetation actively regulates their thermal environment at the plant scale. Also, the cooling was found on air temperature from flux tower comparisons. This further confirms that irrigation changes the microclimate surrounding irrigated crops. However, it should be clarified the irrigation cooling found in our study at small-scale 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, Snyder, & Sloan, 2007; Sacks, Cook, Buenning, Levis, & Helkowski, 2008; Thiery et al., 2017; Lu, Harding, & Kueppers, 2017; Lobell, Bonfils, Kueppers, & Snyder, 2008; Santanello, Peters-Lidard, & Kumar, 2011) (Figure 7). 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 irrigation would not trigger significant changes in background climate state, thereby excluding the atmosphere feedback that may cause non-local impact 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 precipitation pattern if irrigation area becomes sufficiently large, which seems to be already the case in many intensive agriculture areas (e.g., US Corn Belt) (DeAngelis et al., 2010; Szilagyi, 2018; Huber, Mechem, & Brunsell, 2014; Mueller et al., 2015). As a result, irrigation could become a climate forcing that not only drives regional climate change (MAHMOOD et al., 2006; Mueller et al., 2015; Kueppers, Snyder, & Sloan, 2007) but also could have global climate consequences (Sacks, Cook, Buenning, Levis, & Helkowski, 2008). These agricultural practice will interact with climate and then influence crop growth and yields (Butler, Mueller, & Huybers, 2018).

4.4 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 data and method we used. First, there are uncertainties in the thematic classification accuracy of the maize pixels of CDL and the 2005 irrigation facility map which were used to identify the location of irrigated and rainfed maize fields. In addition, our assumption that the field-level irrigation map made for 2005 is also valid for other years could result in some misclassified irrigated and rainfed fields, because some irrigated lands may have been retired, while other areas may have experienced irrigation expansion. Moreover, 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 could be more of an issue for LST (1km) than EVI (250m). To mitigate this issue, we only selected MODIS-scale pixel with the majority of its area composed of 30m irrigated or rainfed maize for analysis. All these factors add up to uncertainty in the extracted signals from satellite remote sensing data for irrigated and rainfed maize. Nevertheless, irrigation effects identified on LST and EVI are unlikely to be significantly altered by these uncertainties, as validation showed reasonable performance (Figs **??** and **??**) and the extracted signals such as LST cooing and EVI increase generally agree with our expectation.

The irrigation benefits on yield are separated into cooling and water supply with statistical models. Since this quantification relies on statistical models, the estimated specific contributions will likely to be different with different model configurations, but the relative importance of cooling and water supply is robust and is not affected by model selection. 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 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 all attributed to water supply. In fact, irrigated and rainfed crops could be different in other aspects such as crop variety (Tack, Barkley, & Hendricks, 2017), management practices, and these factors may also contribute to their yield differences. Therefore, the water supply effect identified here actually includes contributions from water supply and other related factors.

Some important factors of irrigation are not taken into account in our analysis due to lack of data, for example, the amount, timing, and duration of irrigation. In our case, irrigation is considered as a binary situation. As for the actual irrigation practice, we assume that producers would make sensible decisions of their irrigation strategy to maximize their crop yields while being cost-effective. The effects of these granular factors require further investigation.

Our study provides observational evidence of how irrigation changes crop growth and crop properties with satellite remote sensing data (LST, 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 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 climate condition. With projected shifting precipitation patterns, and more frequent droughts and heatwaves in the future (Wuebbles et al., 2017; Huang et al., 2017), a large expansion of irrigation would be required to sustain current maize yield trend in the US (DeLucia et al., 2019; McDonald & Girvetz, 2013), and the irrigation effects will also be intensified. Therefore, the interaction between irrigation effect and climate, as well as the different contributions from cooling and water supply, becomes more essential to understand the consequences of future expanded irrigation on crop production and regional climate.

Acknowledgements

Y.L. acknowledges support from the State Key Laboratory of Earth Surface Processes and Resource Ecology. K.G. acknowledge the support from USDA NIFA projects (2017-67013-26253, 2017-68002-26789, 2017-67003-28703) and NSF CAREER award (#). T.F. acknowledges the support from USDA NIFA project (#???? New project number) and Hatch Project #1009760. The authors declare no conflict of interest for this work.

Author contribution

Y.L. and K.G. conceived and designed the study; T.F. and B.W. provided the 2005 Nebraska irrigation map data. 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.

Supplementary Material

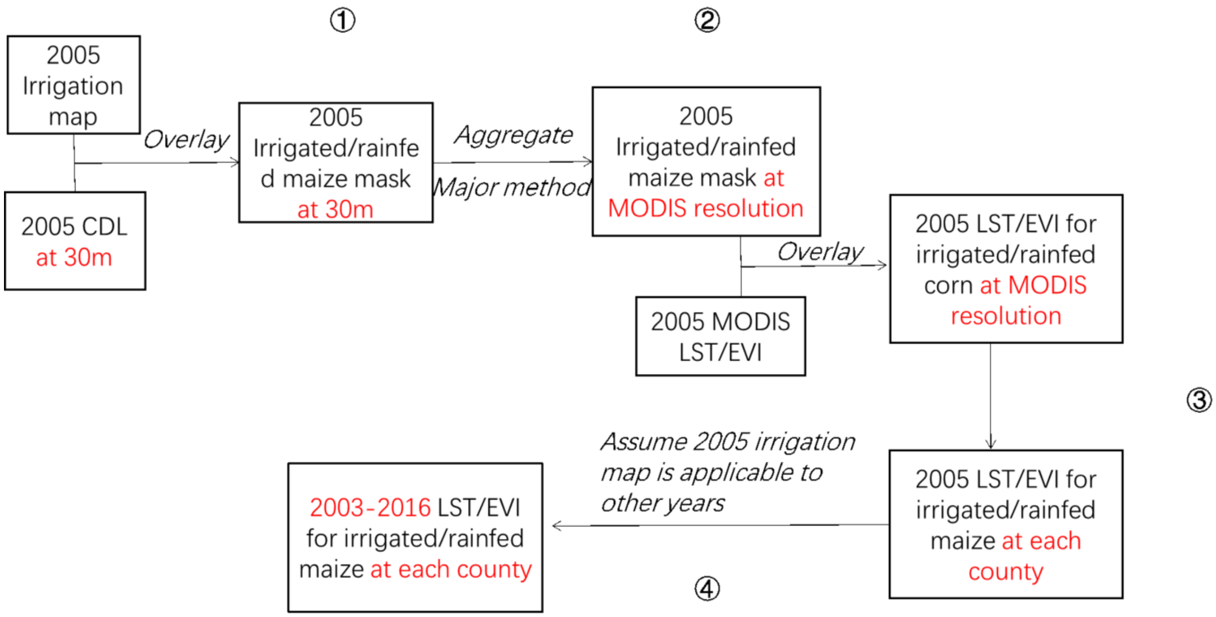

Figure S1: Data processing diagram

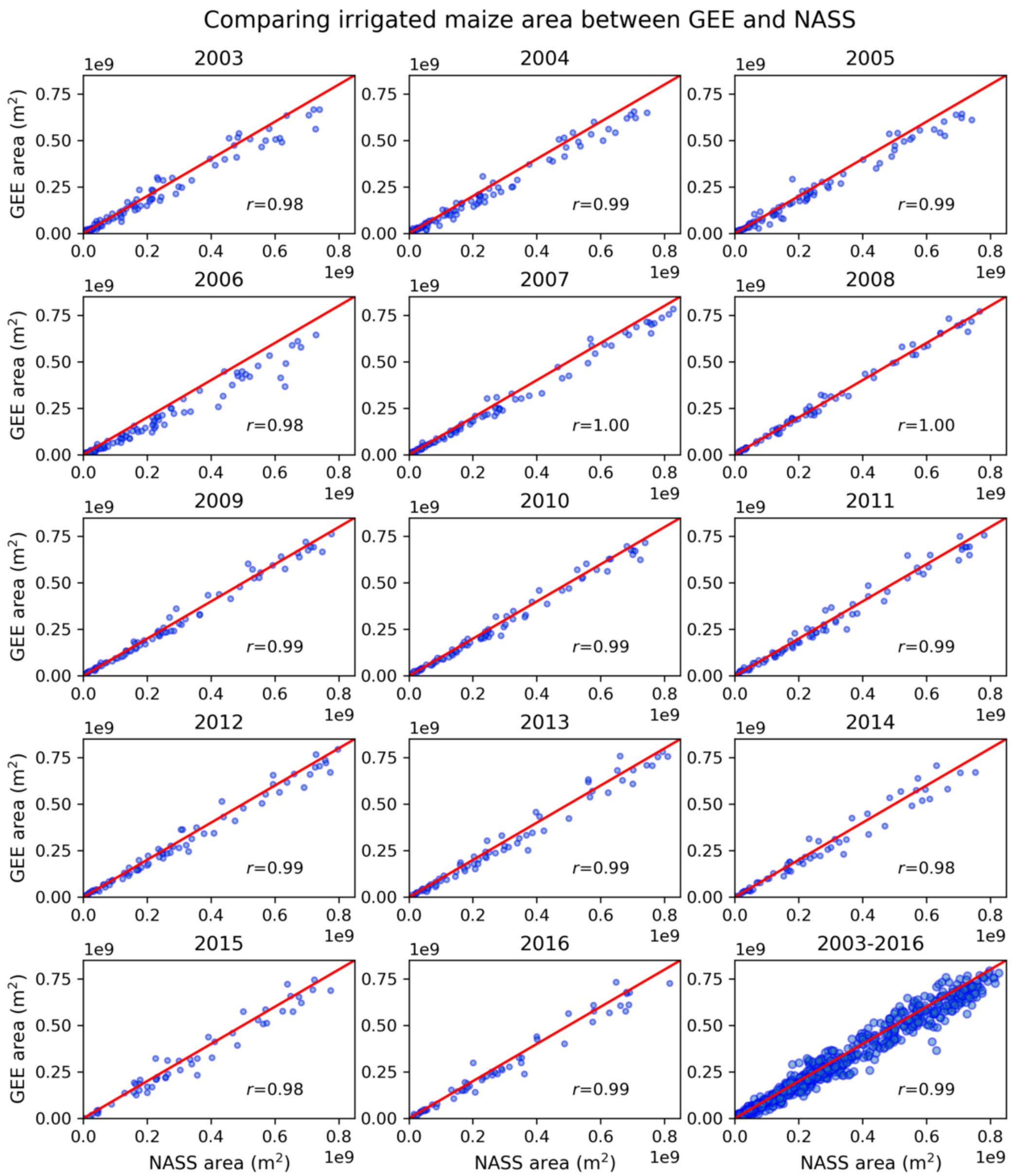

Figure S2: Comparing county-level irrigated maize area derived from GEE and NASS in Nebraska from 2003 to 2016

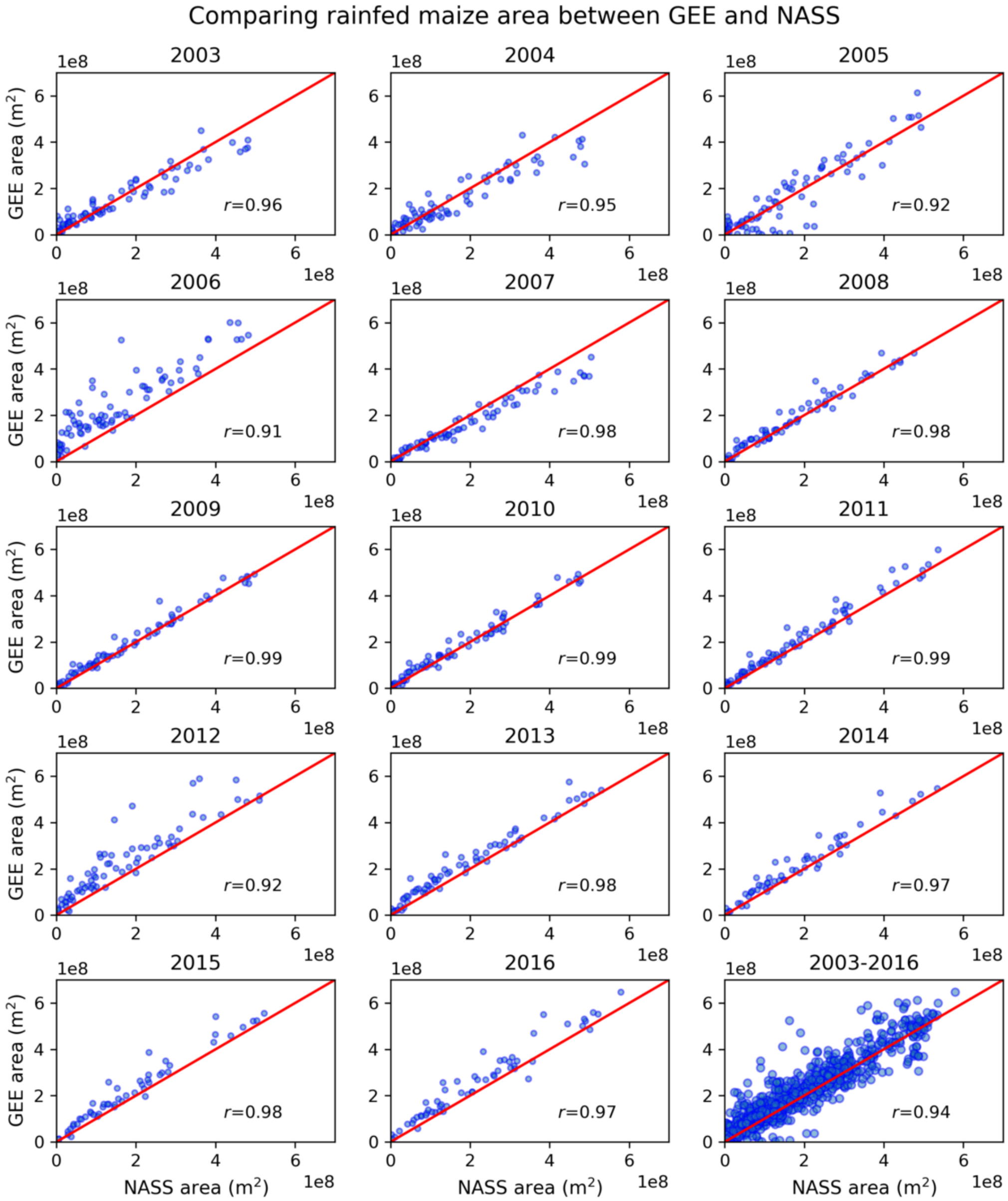

Figure S3: Comparing county-level rainfed maize area derived from GEE and NASS in Nebraska from 2003 to 2016

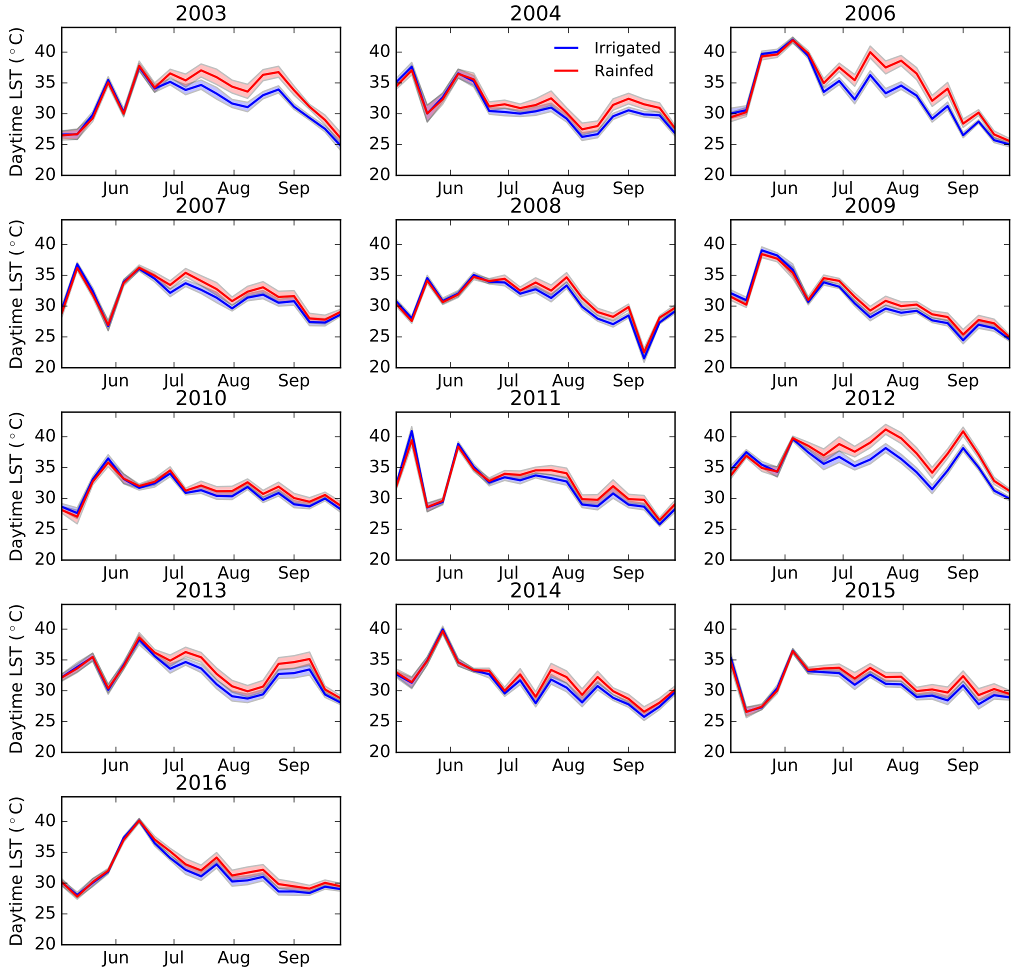

Figure S4: The average LST between irrigated and rainfed maize field in Nebraska in different years

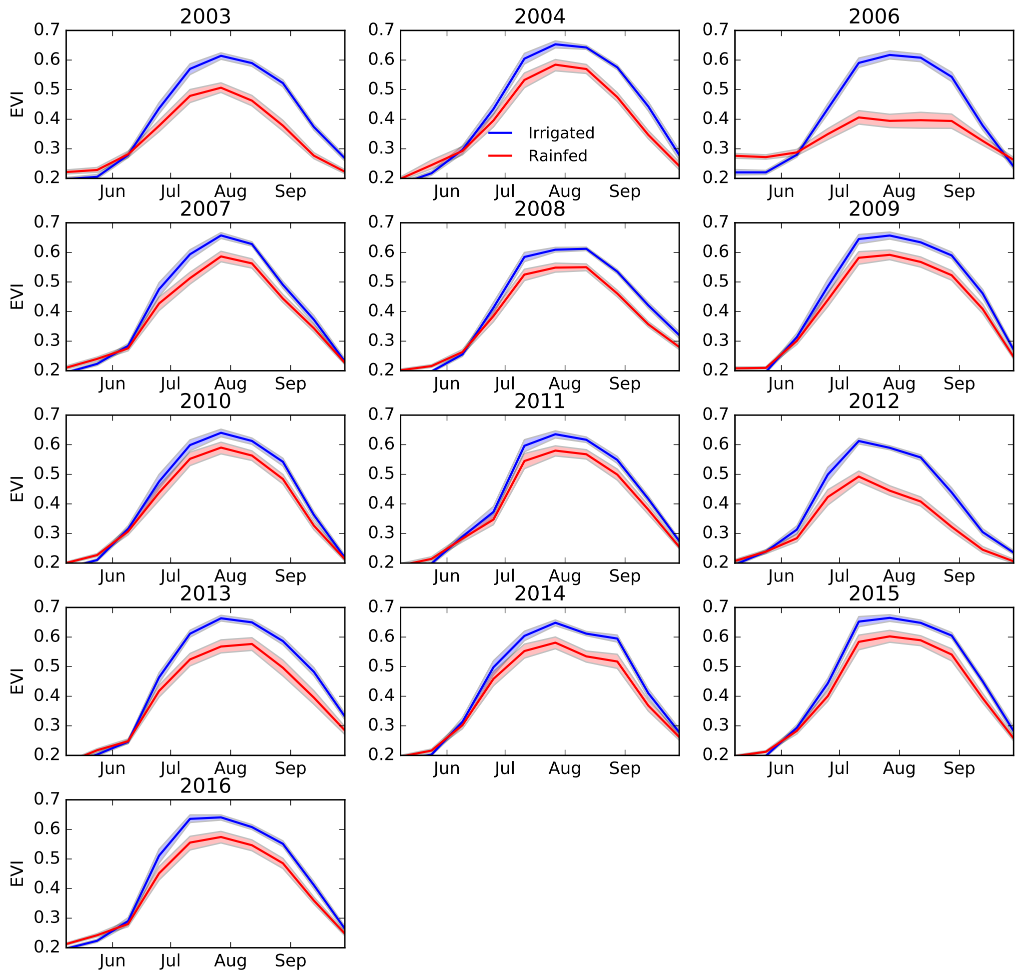

Figure S5: The average EVI between irrigated and rainfed maize field in Nebraska in different years

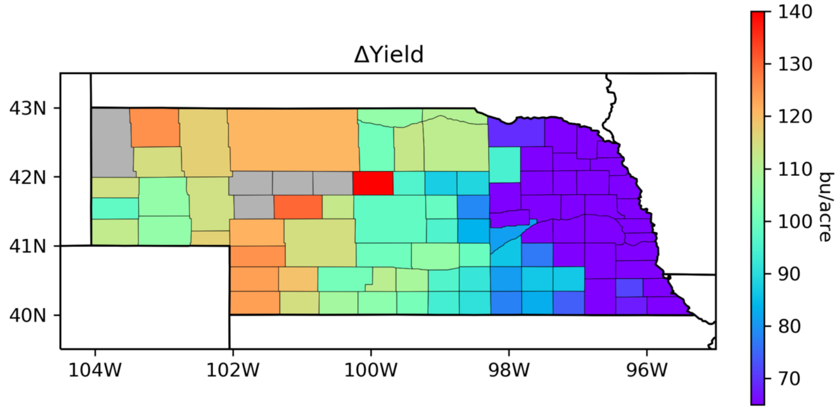

Figure S6: The average yield differences between irrigated and rainfed maize from 2003 to 2016 in Nebraska

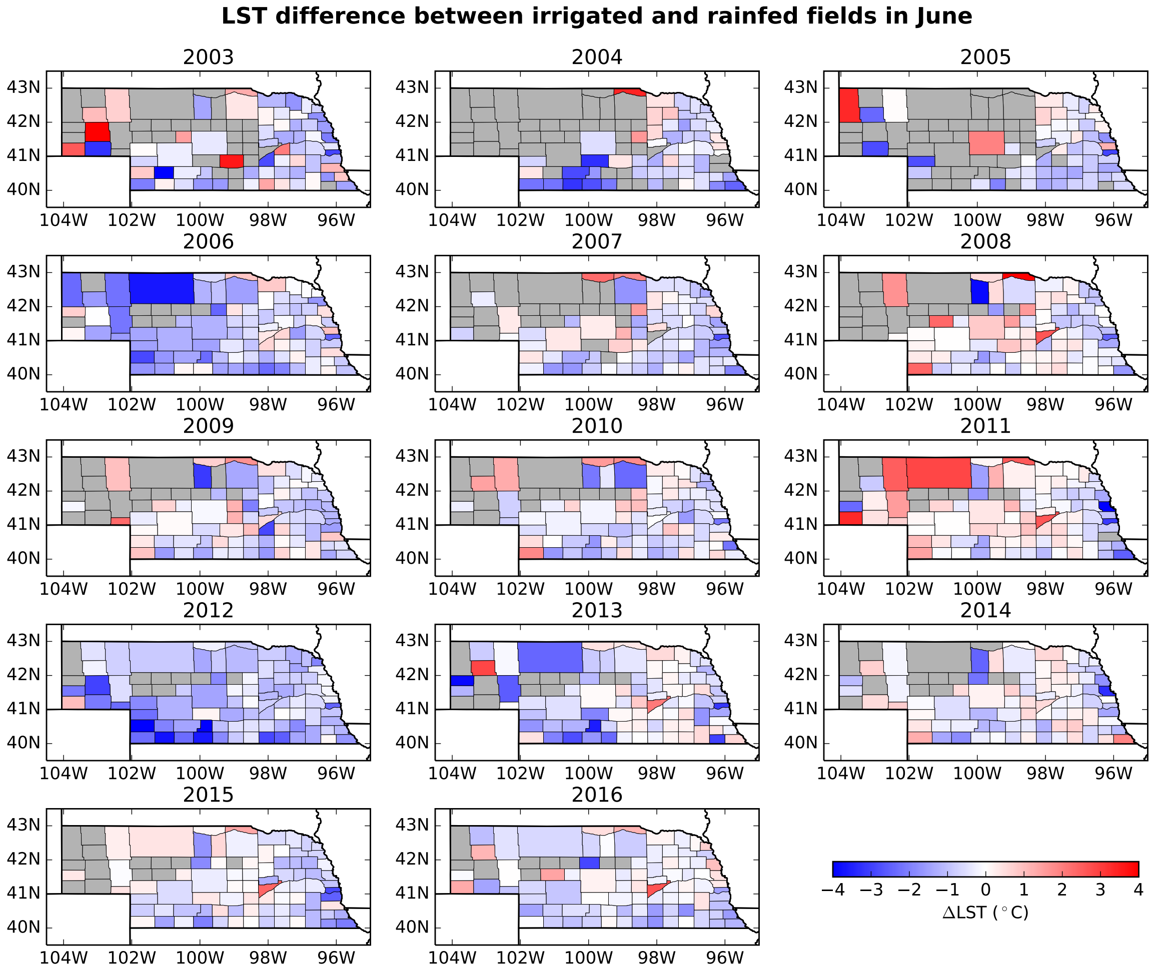

Figure S7: Spatial pattern of June LST difference (ΔLST) from 2003 to 2016

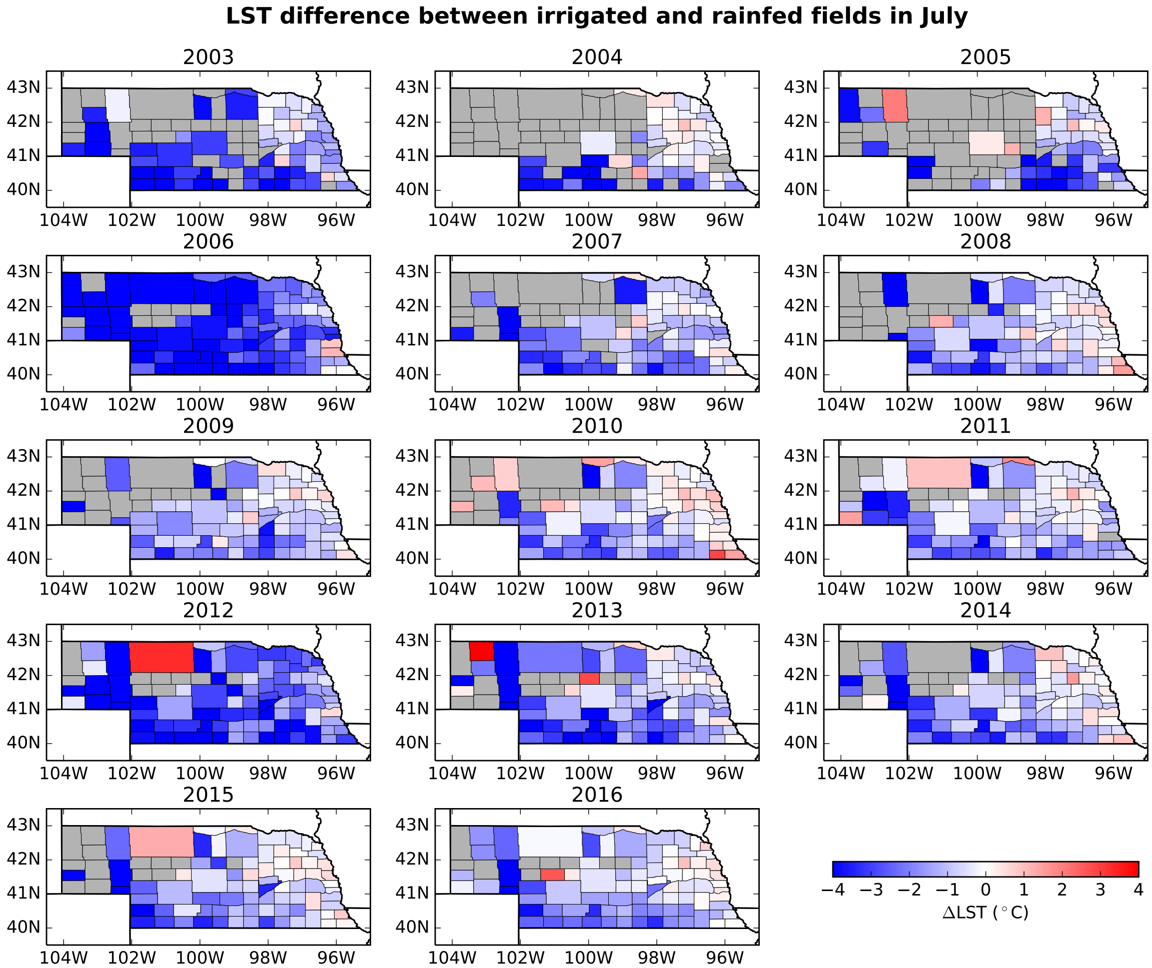

Figure S8: Spatial pattern of July LST difference (ΔLST) from 2003 to 2016

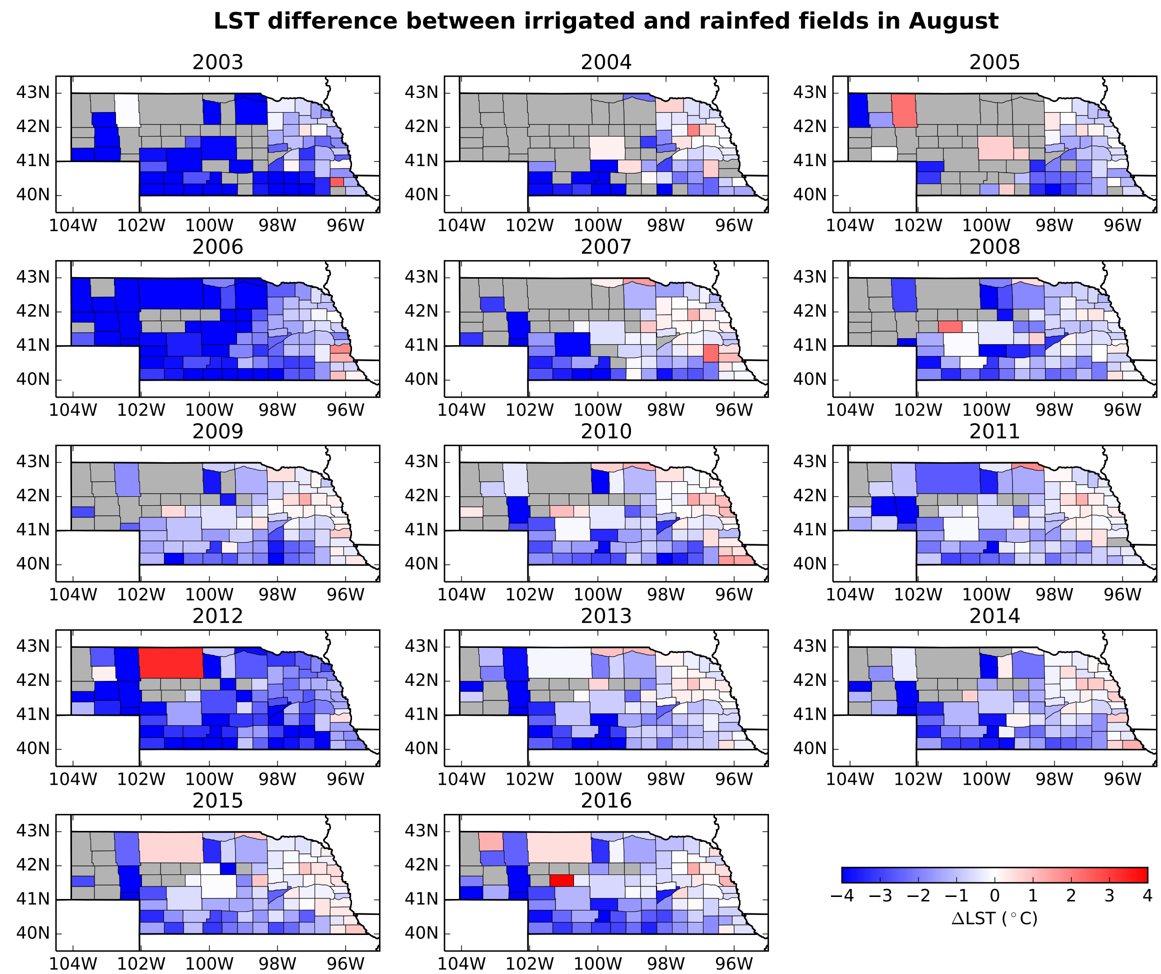

Figure S9: Spatial pattern of August LST difference (ΔLST) from 2003 to 2016

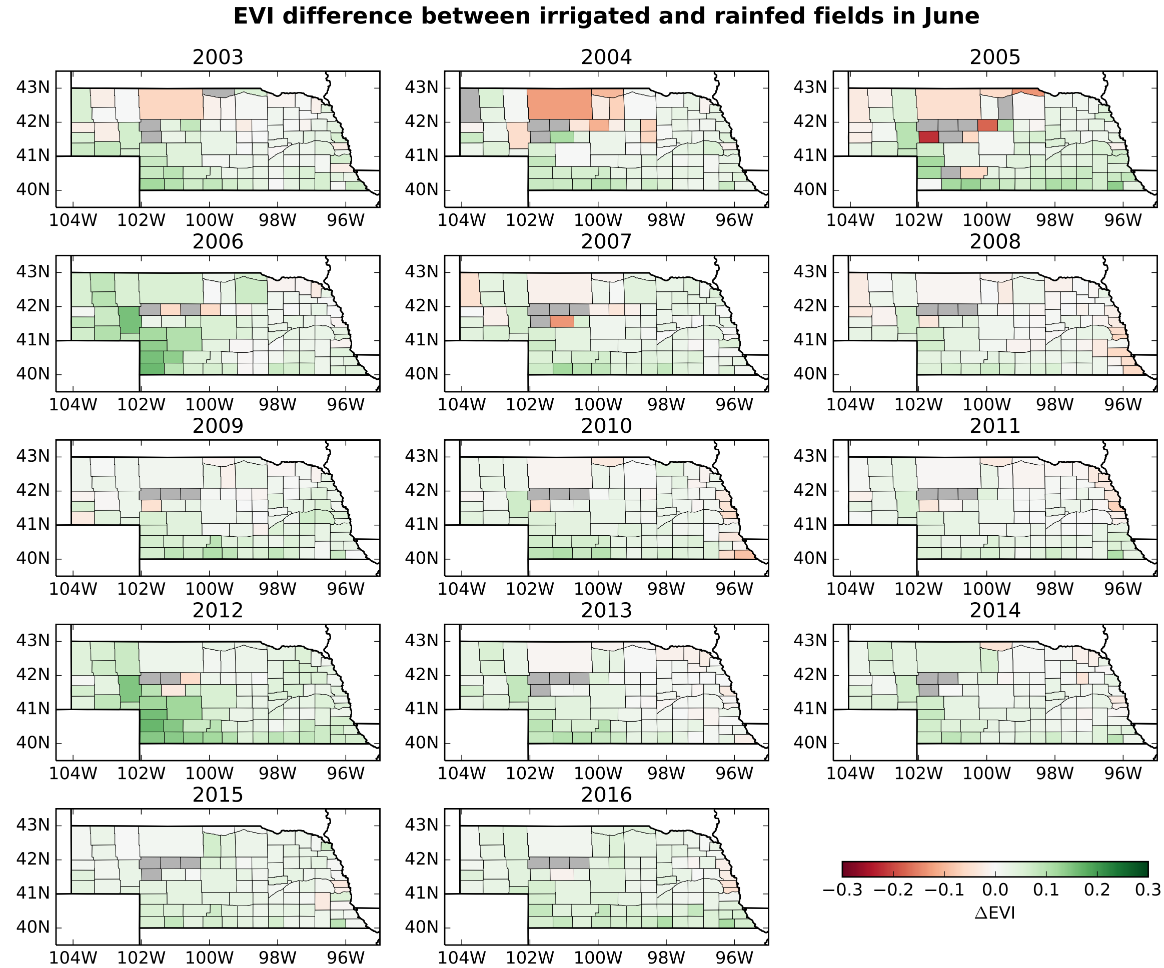

Figure S10: Spatial pattern of June EVI difference (ΔEVI) from 2003 to 2016

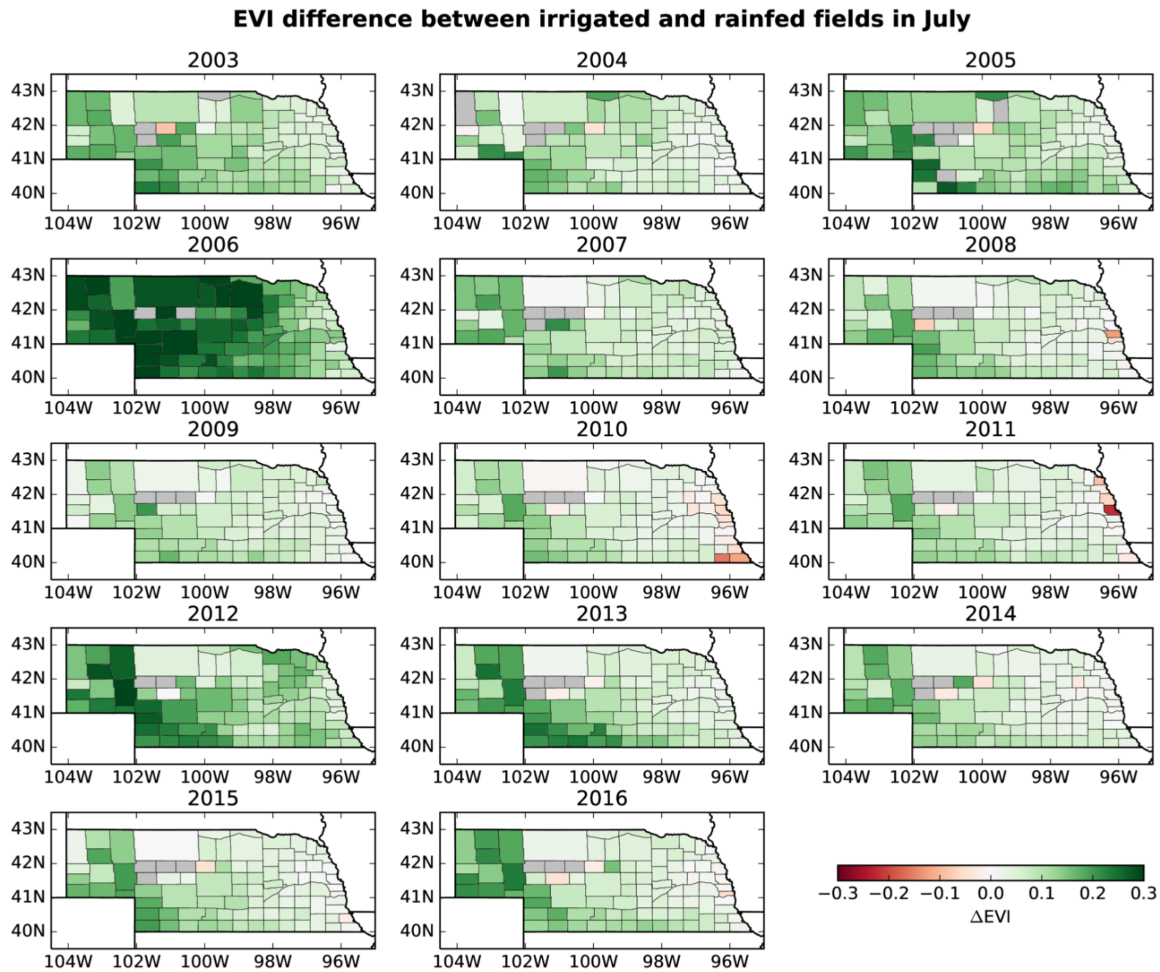

Figure S11: Spatial pattern of July EVI difference (ΔEVI) from 2003 to 2016

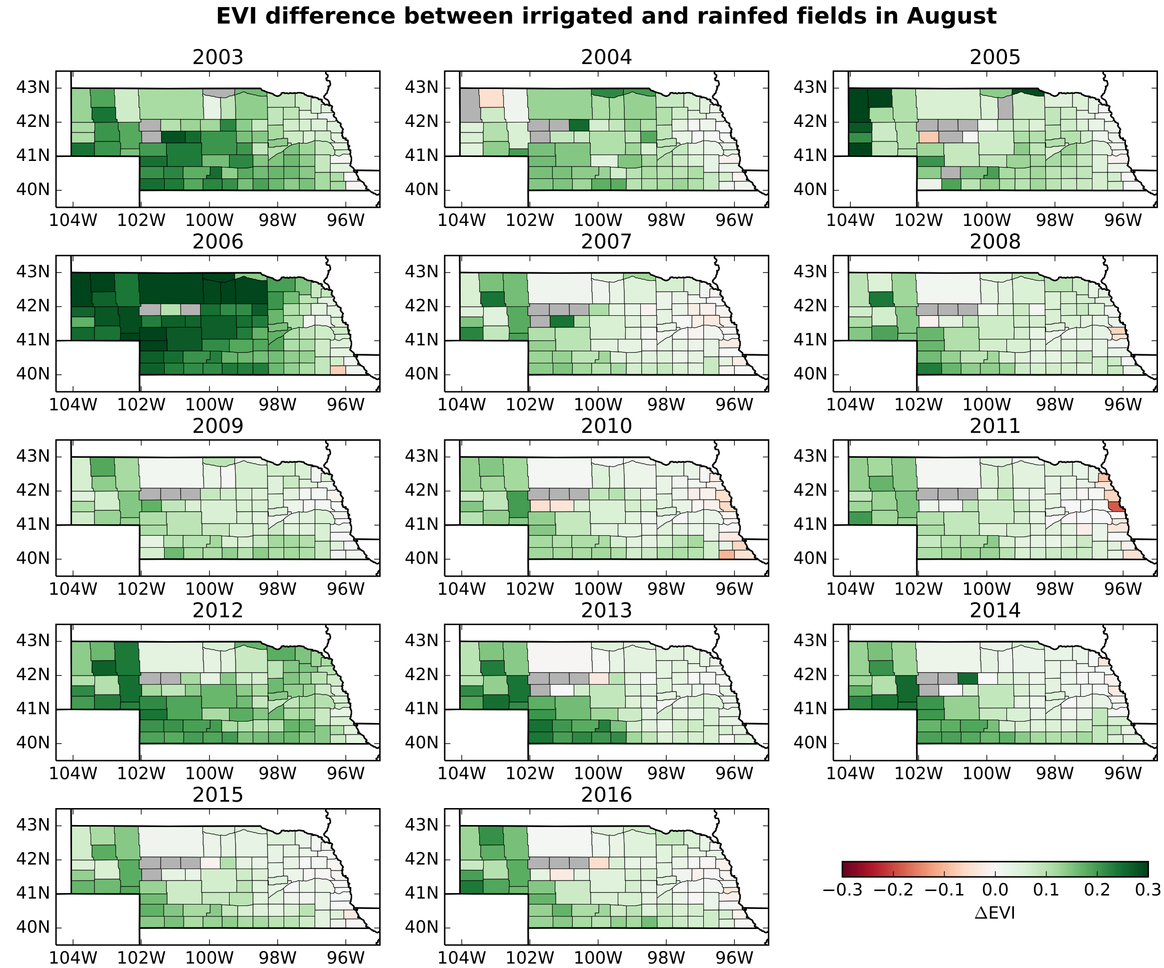

Figure S12: Spatial pattern of August EVI difference (ΔEVI) from 2003 to 2016

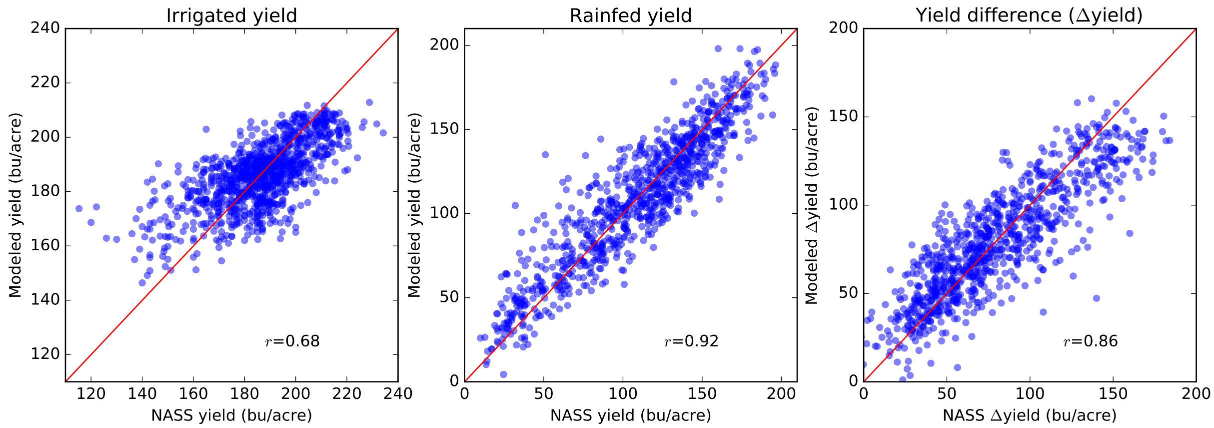

Figure S13: Comparing the modeled irrigated and rainfed yield, and their difference (Δyield) with those from NASS data from 2003 to 2016.

References

U.S. Global Change Research Program*Climate Science Special Report: Fourth National Climate Assessment Volume I*. (2017). https://doi.org/10.7930/j0j964j6

Bonfils, C., & Lobell, D. (2007). Empirical evidence for a recent slowdown in irrigation-induced cooling. *Proceedings of the National Academy of Sciences*, *104*(34), 13582–13587. https://doi.org/10.1073/pnas.0700144104

Butler, E. E., Mueller, N. D., & Huybers, P. (2018). Peculiarly pleasant weather for US maize. *Proceedings of the National Academy of Sciences*, *115*(47), 11935–11940. https://doi.org/10.1073/pnas.1808035115

Carter, E. K., Melkonian, J., Riha, S. J., & Shaw, S. B. (2016). Separating heat stress from moisture stress: analyzing yield response to high temperature in irrigated maize. *Environmental Research Letters*, *11*(9), 094012. https://doi.org/10.1088/1748-9326/11/9/094012

DeAngelis, A., Dominguez, F., Fan, Y., Robock, A., Kustu, M. D., & Robinson, D. (2010). Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. *Journal of Geophysical Research*, *115*(D15). https://doi.org/10.1029/2010jd013892

DeLucia, E. H., Chen, S., Guan, K., Peng, B., Li, Y., Gomez-Casanovas, N., … Ort, D. R. (2019). Are we approaching a water ceiling to maize yields in the United States?. *Ecosphere*, *10*(6), e02773. https://doi.org/10.1002/ecs2.2773

Douglas, E. M., Beltrán-Przekurat, A., Niyogi, D., Pielke, R. A., & Vörösmarty, C. J. (2009). The impact of agricultural intensification and irrigation on land–atmosphere interactions and Indian monsoon precipitation — A mesoscale modeling perspective. *Global and Planetary Change*, *67*(1-2), 117–128. https://doi.org/10.1016/j.gloplacha.2008.12.007

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., … Wisser, D. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change.. *Proc Natl Acad Sci U S A*, *111*, 3239–3244.

Grassini, P., Yang, H., & Cassman, K. G. (2009). Limits to maize productivity in Western Corn-Belt: A simulation analysis for fully irrigated and rainfed conditions. *Agricultural and Forest Meteorology*, *149*(8), 1254–1265. https://doi.org/10.1016/j.agrformet.2009.02.012

Harding, K. J., Twine, T. E., & Lu, Y. (2015). Effects of Dynamic Crop Growth on the Simulated Precipitation Response to Irrigation. *Earth Interactions*, *19*(14), 1–31. https://doi.org/10.1175/ei-d-15-0030.1

Huang, S., Leng, G., Huang, Q., Xie, Y., Liu, S., Meng, E., & Li, P. (2017). The asymmetric impact of global warming on US drought types and distributions in a large ensemble of 97 hydro-climatic simulations. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-06302-z

Huber, D., Mechem, D., & Brunsell, N. (2014). The Effects of Great Plains Irrigation on the Surface Energy Balance Regional Circulation, and Precipitation. *Climate*, *2*(2), 103–128. https://doi.org/10.3390/cli2020103

Jim Jansen, J. S. (2018). *Nebraska Farm Real Estate Market Highlights 2017-2018*. University of Nebraska-Lincoln.

Jin, M., & Dickinson, R. E. (2010). Land surface skin temperature climatology: benefitting from the strengths of satellite observations. *Environmental Research Letters*, *5*(4), 044004. https://doi.org/10.1088/1748-9326/5/4/044004

Katerji, N., Mastrorilli, M., & Rana, G. (2008). Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. *European Journal of Agronomy*, *28*(4), 493–507. https://doi.org/10.1016/j.eja.2007.12.003

Kueppers, L. M., Snyder, M. A., & Sloan, L. C. (2007). Irrigation cooling effect: Regional climate forcing by land-use change. *Geophysical Research Letters*, *34*(3). https://doi.org/10.1029/2006gl028679

Li, Y., Guan, K., Schnitkey, G. D., DeLucia, E., & Peng, B. (2019). Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology*. https://doi.org/10.1111/gcb.14628

Li, Y., Guan, K., Yu, A., Peng, B., Zhao, L., Li, B., & Peng, J. (2019). Toward building a transparent statistical model for improving crop yield prediction: Modeling rainfed corn in the U.S. *Field Crops Research*, *234*, 55–65. https://doi.org/10.1016/j.fcr.2019.02.005

Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., & Li, S. (2015). Local cooling and warming effects of forests based on satellite observations. *Nature Communications*, *6*(1). https://doi.org/10.1038/ncomms7603

Lobell, D. B., Bonfils, C. J., Kueppers, L. M., & Snyder, M. A. (2008). Irrigation cooling effect on temperature and heat index extremes. *Geophysical Research Letters*, *35*(9). https://doi.org/10.1029/2008gl034145

Lobell, D. B., Hammer, G. L., McLean, G., Messina, C., Roberts, M. J., & Schlenker, W. (2013). The critical role of extreme heat for maize production in the United States. *Nature Climate Change*, *3*(5), 497–501. https://doi.org/10.1038/nclimate1832

Lu, Y., Harding, K., & Kueppers, L. (2017). Irrigation Effects on Land–Atmosphere Coupling Strength in the United States. *Journal of Climate*, *30*(10), 3671–3685. https://doi.org/10.1175/jcli-d-15-0706.1

Lu, Y., Jin, J., & Kueppers, L. M. (2015). Crop growth and irrigation interact to influence surface fluxes in a regional climate-cropland model (WRF3.3-CLM4crop). *Climate Dynamics*, *45*(11-12), 3347–3363. https://doi.org/10.1007/s00382-015-2543-z

MAHMOOD, R., FOSTER, S., KEELING, T., HUBBARD, K., CARLSON, C., & LEEPER, R. (2006). Impacts of irrigation on 20th century temperature in the northern Great Plains. *Global and Planetary Change*, *54*(1-2), 1–18. https://doi.org/10.1016/j.gloplacha.2005.10.004

McDonald, R. I., & Girvetz, E. H. (2013). Two challenges for U.S. irrigation due to climate change: increasing irrigated area in wet states and increasing irrigation rates in dry states.. *PLoS One*, *8*, e65589.

Mueller, N. D., Butler, E. E., McKinnon, K. A., Rhines, A., Tingley, M., Holbrook, N. M., & Huybers, P. (2015). Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, *6*(3), 317–322. https://doi.org/10.1038/nclimate2825

Nocco, M. A., Smail, R. A., & Kucharik, C. J. (2019). Observation of irrigation-induced climate change in the Midwest United States. *Global Change Biology*. https://doi.org/10.1111/gcb.14725

Oweis, T., Zhang, H., & Pala, M. (2000). Water Use Efficiency of Rainfed and Irrigated Bread Wheat in a Mediterranean Environment. *Agronomy Journal*, *92*(2), 231. https://doi.org/10.2134/agronj2000.922231x

Payero, J. O., Tarkalson, D. D., Irmak, S., Davison, D., & Petersen, J. L. (2008). Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration yield, water use efficiency, and dry matter production in a semiarid climate. *Agricultural Water Management*, *95*(8), 895–908. https://doi.org/10.1016/j.agwat.2008.02.015

Peng, B., Guan, K., Chen, M., Lawrence, D. M., Pokhrel, Y., Suyker, A., . . . Lu, Y. (2018). Improving maize growth processes in the community land model: Implementation and evaluation. *Agricultural and Forest Meteorology*, *250-251*, 64–89. https://doi.org/10.1016/j.agrformet.2017.11.012

Sacks, W. J., Cook, B. I., Buenning, N., Levis, S., & Helkowski, J. H. (2008). Effects of global irrigation on the near-surface climate. *Climate Dynamics*, *33*(2-3), 159–175. https://doi.org/10.1007/s00382-008-0445-z

Santanello, J. A., Peters-Lidard, C. D., & Kumar, S. V. (2011). Diagnosing the Sensitivity of Local Land–Atmosphere Coupling via the Soil Moisture–Boundary Layer Interaction. *Journal of Hydrometeorology*, *12*(5), 766–786. https://doi.org/10.1175/jhm-d-10-05014.1

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change.. *Proc Natl Acad Sci U S A*, *106*, 15594–15598.

Sharma, V., & Irmak, S. (2012). Mapping Spatially Interpolated Precipitation Reference Evapotranspiration, Actual Crop Evapotranspiration, and Net Irrigation Requirements in Nebraska: Part I. Precipitation and Reference Evapotranspiration. *Transactions of the ASABE*, *55*(3), 907–921. https://doi.org/10.13031/2013.41523

Sharma, V., & Irmak, S. (2012). Mapping Spatially Interpolated Precipitation Reference Evapotranspiration, Actual Crop Evapotranspiration, and Net Irrigation Requirements in Nebraska: Part II. Actual

Crop Evapotranspiration and Net Irrigation Requirements. *Transactions of the ASABE*, *55*(3), 923–936. https://doi.org/10.13031/2013.41524

Shaw, S. B., Mehta, D., & Riha, S. J. (2014). Using simple data experiments to explore the influence of non-temperature controls on maize yields in the mid-West and Great Plains. *Climatic Change*, *122*(4), 747–755. https://doi.org/10.1007/s10584-014-1062-y

Siebert, S., Ewert, F., Rezaei, E. E., Kage, H., & Graß, R. (2014). Impact of heat stress on crop yield—on the importance of considering canopy temperature. *Environmental Research Letters*, *9*(4), 044012. https://doi.org/10.1088/1748-9326/9/4/044012

Siebert, S., Webber, H., Zhao, G., & Ewert, F. (2017). Heat stress is overestimated in climate impact studies for irrigated agriculture. *Environmental Research Letters*, *12*(5), 054023. https://doi.org/10.1088/1748-9326/aa702f

Suyker, A. E., & Verma, S. B. (2012). Gross primary production and ecosystem respiration of irrigated and rainfed maize–soybean cropping systems over 8 years. *Agricultural and Forest Meteorology*, *165*, 12–24. https://doi.org/10.1016/j.agrformet.2012.05.021

Suyker, A. E., Verma, S. B., Burba, G. G., & Arkebauer, T. J. (2005). Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season. *Agricultural and Forest Meteorology*, *131*(3-4), 180–190. https://doi.org/10.1016/j.agrformet.2005.05.007

Szilagyi, J. (2018). Anthropogenic hydrological cycle disturbance at a regional scale: State-wide evapotranspiration trends (1979–2015) across Nebraska USA. *Journal of Hydrology*, *557*, 600–612. https://doi.org/10.1016/j.jhydrol.2017.12.062

Tack, J., Barkley, A., & Hendricks, N. (2017). Irrigation offsets wheat yield reductions from warming temperatures. *Environmental Research Letters*, *12*(11), 114027. https://doi.org/10.1088/1748-9326/aa8d27

Thiery, W., Davin, E. L., Lawrence, D. M., Hirsch, A. L., Hauser, M., & Seneviratne, S. I. (2017). Present-day irrigation mitigates heat extremes. *Journal of Geophysical Research: Atmospheres*, *122*(3), 1403–1422.

https://doi.org/10.1002/2016jd025740

Troy, T. J., Kipgen, C., & Pal, I. (2015). The impact of climate extremes and irrigation on US crop yields. *Environmental Research Letters*, *10*(5), 054013. https://doi.org/10.1088/1748-9326/10/5/054013

Vogel, E., Donat, M. G., Alexander, L. V., Meinshausen, M., Ray, D. K., Karoly, D., … Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, *14*(5), 054010. https://doi.org/10.1088/1748-9326/ab154b

Walker, W. R. (1989). The practice of irrigation. In *Guidelines for designing and evaluating surface irrigation systems*. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO).

Winckler, J., Lejeune, Q., Reick, C. H., & Pongratz, J. (2019). Nonlocal Effects Dominate the Global Mean Surface Temperature Response to the Biogeophysical Effects of Deforestation. *Geophysical Research Letters*, *46*(2), 745–755. https://doi.org/10.1029/2018gl080211

Wu, L., Feng, J., & Miao, W. (2018). Simulating the Impacts of Irrigation and Dynamic Vegetation Over the North China Plain on Regional Climate. *Journal of Geophysical Research: Atmospheres*. https://doi.org/10.1029/2017jd027784

Zhu, X., Liang, S., & Pan, Y. Z. (2012). Observational evidence of the cooling effect of agricultural irrigation in Jilin China. *Climatic Change*, *114*(3-4), 799–811. https://doi.org/10.1007/s10584-012-0435-3