communications earth & environment

A Nature Portfolio journal

Article

https://doi.org/10.1038/s43247-025-02459-y

Increased irrigation could mitigate future warming-induced maize yield losses in the Ogallala Aquifer

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Irrigation is a fundamental practice for mitigating crop yield losses from drought and heat extremes. However, the extent to which irrigation moderates crop sensitivity to these stresses and the future quantity of irrigation required to maintain crop yields remain unclear. Here, we use a meta-analysis of maize field experiments across the Ogallala Aquifer to quantify how varying irrigation amounts influence yield sensitivity to heat and drought based on a panel regression model. We find that each 100 mm increase in irrigation reduces heat sensitivity of maize by 7.6%. By the 2050s, offsetting a projected 26% yield decline under a high-emission scenario, primarily driven by intensifying heat stress, would require a 67% increase in irrigation amounts. These findings provide key insights into the interplay between irrigation and climatic extremes, highlighting the urgent need for efficient irrigation strategies to balance crop yield and water resource sustainability.

Climate change, characterized by rising temperatures, intensifying droughts, flooding, and increasing heatwaves, poses a threat to agricultural productivity and global food security[1–4]. Over the past decade, these climatic extremes have caused estimated losses of $30 billion in global crop production[5], highlighting the vulnerability of existing agricultural systems. Projections suggest that future climates will be even hotter and drier[6], further exacerbating threats to crop yields[7,8]. In response, farmers have increasingly adopted adaptive practices to safeguard food production, with irrigation emerging as a long-term, primary option[9–11]. By stabilizing crop water supply and mitigating heat stress, irrigation plays a critical role in sustaining food production, particularly in arid and semi-arid regions highly susceptible to climate change impacts[12].

Irrigated agriculture is generally more productive in terms of crop yields than rain-fed agriculture[13]. However, it also drives immense water demands, accounting for approximately 70% of global freshwater withdrawals[14,15]. As temperatures rise, farmers may further intensify irrigation to meet the increased water needs of crops, accelerating groundwater depletion and straining water availability[16–18]. One example of how this is occurring is in the U.S. Ogallala Aquifer[19,20], one of the world's largest and most productive aquifers. Spanning 450,660 km^2 across eight states (Fig. 1)[19], the Ogallala Aquifer supports 30% of U.S. crop and livestock production, contributing $1.75 billion to maize production and driving a $35 billion agricultural industry each year[18,21]. Yet, decades of intensive groundwater extraction for irrigation have caused widespread water-level declines, raising urgent concerns about the sustainability of water resources and agricultural systems in the face of future climate change[18,20,22].

Amid the dual pressures of climate change threatening crop yields and accelerating global groundwater depletion[23], a nuanced understanding of irrigation's ability to maintain crop yields in the face of increasing heat and drought stress is vital. A large and growing body of literature has documented the benefits of irrigation in mitigating the effects of climatic extremes on crop yields at regional and national levels[9–11,24–27]. However, due to the limited availability of data on the amounts of irrigation during the crop growing season across a large regional scale, these studies typically rely on coarse water management information (irrigated *vs.* rainfed) and concluded that irrigation can offset yield losses caused by adverse climate. For example, Tack et al.[28] found that a 1°C temperature increase reduces U.S. wheat yields by 6% under rainfed conditions, while such losses are completely offset under irrigation conditions. More recent studies[10,29] have incorporated irrigation area proportions, defined as the fraction of cropped area that is irrigated within each district, to account for the role of irrigation in reducing crop vulnerability to climate extremes.

Despite these efforts, there remains uncertainty in quantifying the specific irrigation amounts (Irr) needed to mitigate crop sensitivity to heat or drought. Better understanding this mitigation effect is crucial for improving climate impact projections and optimizing irrigation management practices

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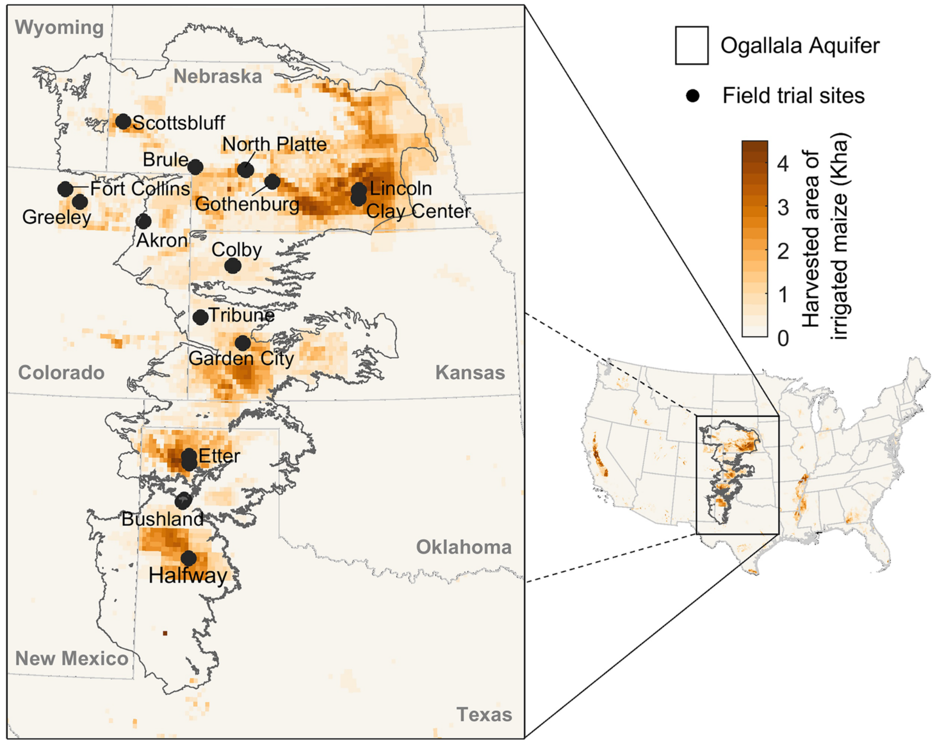

Fig. 1 | Map showing the locations of experimental sites (black dots) used for irrigated maize studies in our meta-analysis. The background color gradient represents the harvested area of irrigated maize at 5 min resolution around 2015 (2014–2016), and the outlined region indicates the Ogallala Aquifer domain.

for sustainable water use, as well as food security[30]. These two interacting subjects are our primary study foci: irrigation (underground water savings of the Ogallala Aquifer) and crop production. Most current studies lack long-term observation data on Irr at the regional scale, meaning that the simplified estimates of irrigation used in those studies could introduce uncertainties when assessing the extent to which irrigation can alleviate heat sensitivity[28,31]. Additionally, the lack of quality irrigation data in previous studies at the regional scale limits their ability to capture the dynamic of actual water supply, leading to uncertain assessments of drought impacts on crop yields[32]. Recent studies also emphasize the need for further study to better understand irrigation as an adaptation strategy[25,28,31], particularly in large-scale studies[25,28].

Here, we confront this challenge by performing a meta-analysis of field experiments on irrigated maize across the U.S. Ogallala Aquifer region, which serves as a case study to explore the role of irrigation in enhancing crop resilience to climatic extremes (Fig. 1 and Supplementary Table 1). The dataset includes 707 observations from 33 studies with specific Irr (mm) and management practices (see Methods for data selection). Our analysis focused on maize because of its extensive irrigated harvested area and larger water needs than some other economically viable crops in the U.S. Great Plains[33]. Using this observed dataset, we developed a panel regression model to investigate the relationship between irrigated maize yields, climate variables, and Irr during the growing season. The main objectives of this study are to: (1) quantify the extent to which varying Irr mitigate heat sensitivity and drought impacts; (2) project impacts of future climate change on irrigated maize yields and decompose the contribution of climate drivers; and (3) estimate the additional Irr required to counteract climate change-induced yield losses, which, in turn, will impact groundwater depletion rates.

Results

Irrigated maize yield responses to climate variables

To assess how irrigated maize yields respond to climate variables, we used a linear mixed-effects model that incorporated Irr as a factor, along with nonlinear terms and interactions (Eq. 1 and Supplementary Table 2). Water stress was quantified by defining a water stress index, calculated as the ratio of water supply (precipitation (Prcp) + Irr) to potential evapotranspiration (pET), where a smaller ratio indicates greater insufficiency of water to meet water demand. This approach captures the direct effect of irrigation on maize yield by increasing water supply and alleviating water stress. Our results showed a nonlinear yield response to this ratio, which aligns with the response based on observed data (Fig. 2a,b). By integrating actual Irr alongside Prcp across diverse climatic conditions, our study provides robust empirical evidence of how water supply influences maize yields at a regional scale. Under conditions of water deficits, yields increased rapidly as the ratio rose, whereas with greater water availability, yield gains gradually diminished (Fig. 2b). This saturation effect underscores the importance of optimizing irrigation strategies by integrating Prcp patterns to balance water supply and crop demand, while aligning water management with economic goals to enhance farm profitability and promote sustainable resource use.

To estimate how irrigation modulates yield sensitivity to extreme heat, we included an interaction term between extreme degree days (EDD) (EDD; °C days), defined as accumulation of degree days above 30 °C[34,35], and Irr in the model (Eq. 1). The estimated yield sensitivity to EDD $\left(\frac{\partial Yield}{\partial EDD}\right)$ depends on Irr and can be expressed as $\frac{\partial Yield}{\partial EDD} = \beta_2 + \beta_6 Irr$, where β_2 and β_6 represent the coefficients for EDD and Irr × EDD, respectively (see Methods). A positive β_6 indicates that irrigation alleviates the heat impact, and vice versa. Our analysis showed a negative, statistically significant coefficient for EDD (-0.041 t ha^{-1} per [°C days]; p value < 0.05), indicating a negative effect of heat stress on maize yield. However, the positive, statistically significant coefficient for the interaction term between Irr and EDD (0.0031 ha^{-1} per [100 mm °C days]; p value < 0.05) suggests that increasing irrigation mitigates this negative impact of heat stress on maize yield (Supplementary Table 2). Importantly, we revealed the dynamic role of irrigation in mitigating yield sensitivity to heat stress. Without irrigation (Irr = 0 mm), a unit increase in EDD was associated with an average yield decline of 0.041 t ha^{-1} (Fig. 2c and Supplementary Table 2). Increasing Irr mitigated this sensitivity, with each additional 100 mm of irrigation reducing the yield sensitivity to EDD by 7.6% on average (Fig. 2c and Supplementary Table 2).

Projected climate-driven changes in irrigated maize yield

We assessed the impact of climate change on irrigated maize yield by the 2050s (2050–2059) under four shared socioeconomic pathways (SSPs) (SSP126, SSP245, SSP370, and SSP585) relative to the historical period (2010–2019) (see Methods). To establish a baseline, we first estimated the irrigation amounts required to achieve the current irrigated maize yields

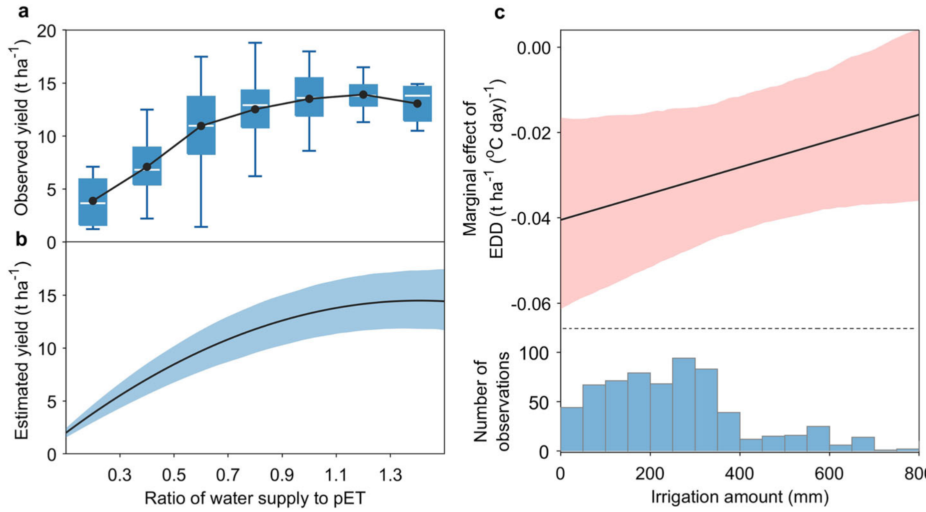

Fig. 2 | Response of irrigated maize yield to ratio of water supply (precipitation + irrigation) to potential evapotranspiration (pET) and extreme degree days (EDD). a Observed yield categorized into seven bins based on the ratio of water supply to pET. Boxplots indicate the median (white line), the mean (black dots), and 25–75th percentiles (box) and 5–95th percentiles (whiskers). **b** Simulated yield response to the ratio of water supply to pET, estimated using a linear-mixed effects model. **c** Sensitivity of yield to EDD as a function of irrigation amount, illustrated through the interaction term between EDD and irrigation amount. The histogram shows the distribution of irrigation amounts sampled. In (**b**) and (**c**), the solid black line represents the average effect, with the shaded area indicating the 2.5–97.5th percentile ranges based on 1000 bootstrapped samples.

(Supplementary Fig. 1) across various grid cells of the Ogallala Aquifer. We quantified irrigation demands of 339 mm on average (ranging from 50 to 550 mm; Fig. 3a), with the larger values observed in the southern regions due to lower growing-season Prcp and greater evapotranspiration rates compared to those in the northern regions (Supplementary Fig. 2). We also calculated state-level average irrigation amounts and compared these estimates with observed state-level data from the USDA-NASS Census of Irrigation, which provides crop-specific irrigation information. Results showed a similar spatial pattern between observed and estimated irrigation amounts (correlation equals to 0.93), with an average absolute difference across states being 30 mm (Supplementary Fig. 3), reinforcing the reliability of our estimates. These baseline irrigation levels were used to predict yield changes under future's climates.

To project the potential impacts of climate change on maize yields, we developed two assumptions regarding farmer responses: (1) "fixed GDD," where farmers continue to use maize hybrids with current growing degree day (GDD) requirements; and (2) "fixed phenology," where farmers attempt to maintain current phenology by selecting hybrids with larger GDD requirements (Methods and Supplementary Fig. 4). Note that, both assumptions maintain constant planting dates based on local historical averages. Under the "fixed GDD," average maize yields are projected to decline by 20% under the low-warming scenario (SSP126) and by up to 32% under the greatest warming scenario (SSP585) (Fig. 3b). Spatially, yield losses are most severe in northeastern regions of the Ogallala Aquifer, reaching up to 50%, while southwestern regions exhibit smaller yield losses, generally below 20% (Fig. 3c). Although the "fixed phenology" assumption alleviates yield losses by an average of 6% (Fig. 3b), climate change-induced yield declines persist, ranging from 14% under SSP126 to 26% under SSP585 (Fig. 3b). The larger yield losses under the "fixed GDD" assumption are primarily attributed to accelerated crop development under higher temperature, which allows hybrids to meet GDD requirements in fewer days[36,37]. This shortens the effective duration of growing season by 5–35 days from south to north (Supplementary Fig. 5a), reducing accumulated radiation and, consequently, yields. Given the ongoing depletion of water resources in this region, we also simulated yield changes under the "fixed phenology" assumption with future irrigation amounts limited to 75% of the local historical levels. The results indicated that yield losses increase by an additional 10% (Supplementary Fig. 6), highlighting the dual challenges of water scarcity and climate change for sustaining maize yields.

Decomposing climate drivers under the "fixed phenology" assumption

Given that maintaining current phenology by selecting greater-GDD hybrids results in smaller yield losses compared to maintaining current GDD hybrids, we focused our subsequent analyses under "fixed phenology" assumption. We decomposed the future yield variability attributed to changes in specific climate variables (Methods). Our results suggest that warmer temperatures have dual, counteracting effects on yields, even when hybrids with greater GDD requirements are used. On the one hand, the ensemble mean shows that an increase in GDD under SSP126 and SSP585 would theoretically work to have a positive effect on yields of 9% and 13%, respectively (Fig. 4a). In addition, greater surface solar radiation (SSR) under all future climate scenarios would contribute an average of 5% to yield gains. However, these yield benefits will be counteracted by two main factors: (1) increased extreme heat stress (EDD), resulting in yield declines of 19 and 31% for SSP126 and SSP585, respectively; and (2) increased water stress associated with increased temperature and evapotranspiration rates, which would reduce yields by 9 and 13% for SSP126 and SSP585, respectively. Taken together, future climate changes are projected to result in average yield losses of 14 and 26% for SSP126 and SSP585, respectively (Fig. 3b), with heat stress identified as the dominant driver (Fig. 4a). The counteracting effects of increased temperature on maize yields differ spatially within the Ogallala Aquifer. For example, under SSP585, in the northern regions, particularly Nebraska, the positive effect on yields from the increase in GDD are more pronounced than in the southern regions (Fig. 4b–e). However, the northern regions will also face severe yield losses from increased water stress (~15%; Fig. 4e) and heat stress (~40%; Fig. 4c). Similar spatial patterns in the decomposition of climate drivers for other scenarios are also presented in Supplementary Fig. 7.

Future irrigation requirements to offset maize yield losses under the "fixed phenology" assumption

We assessed the additional irrigation required by the 2050s to fully offset climate change-induced yield losses. We first estimated future irrigation requirements to maintain current maize yield levels, and then calculated the difference from current irrigation needs. Results indicated that the spatial pattern of projected future irrigation (Supplementary Fig. 8) is similar to the current irrigation pattern (Fig. 3a). We projected that under high-emission scenario (SSP585), the average irrigation amounts by the 2050s will be 567 mm (ranging from 300 to 700 mm; Supplementary Fig. 8), which is 67% larger than the current average. Specifically, the ensemble means of additional irrigation required to offset climate-induced yield loss (Fig. 3d) are 131, 154, 202, and 228 mm under SSP126, SSP245, SSP370, and SSP585, respectively (Fig. 5a), with northeastern regions requiring up to an additional 350 mm under high-emission scenarios (Fig. 5b) due to greater yield declines (Fig. 3d).

Discussion

Despite the recognized potential of irrigation to alleviate the impacts of heat and water stresses in crops[10,28,38], the extent to which varying irrigation

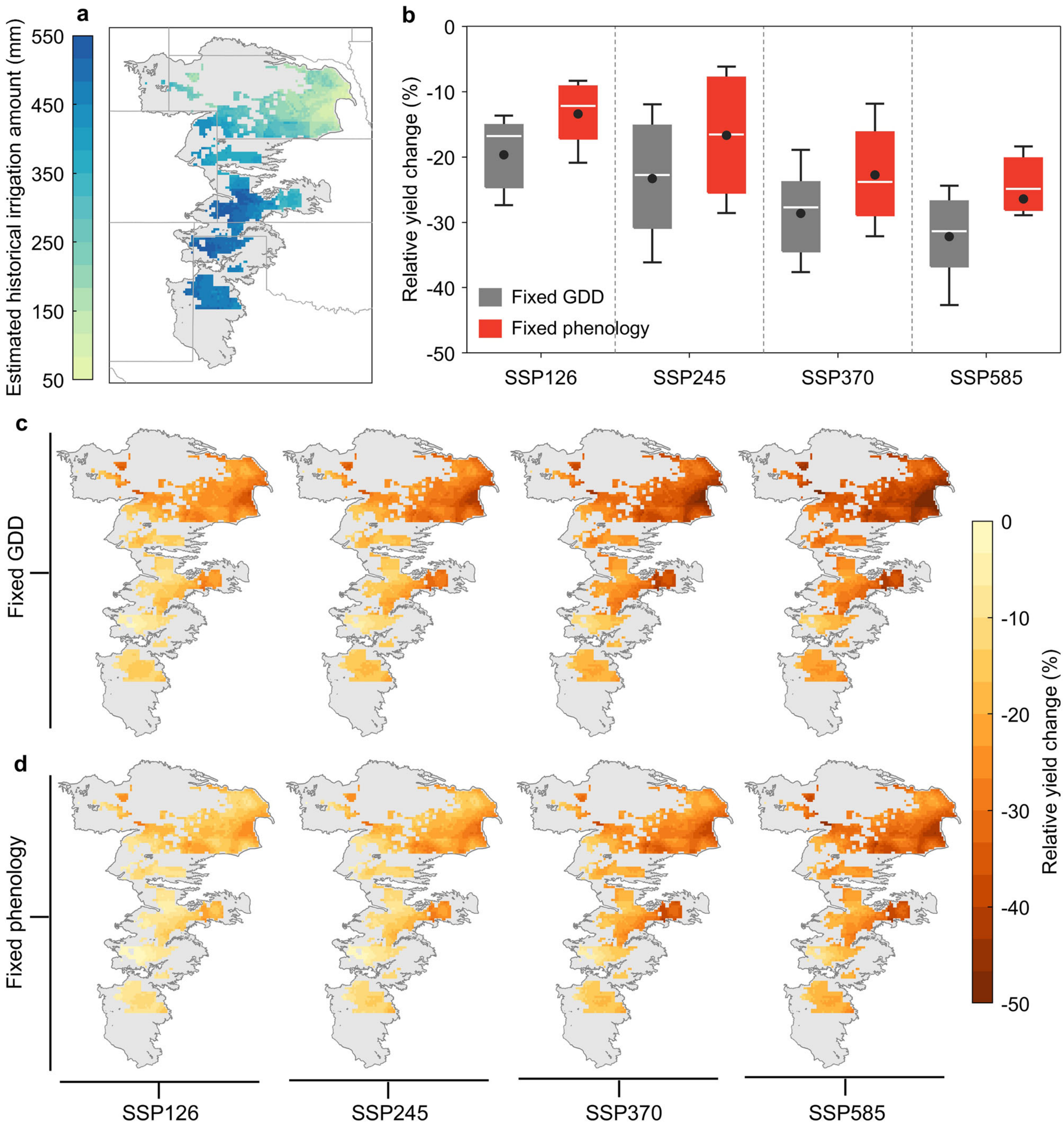

Fig. 3 | Projected climate-driven change in irrigated maize yield for 2050–2059 relative to the reference period 2010–2019 under SSP126, SSP245, SSP370, and SSP585 scenarios. a Estimated averaged current irrigation amount during the 2010s. **b** Projected climate-induced yield changes relative to current yields based on two assumptions: fixed growing degree days (GDD) at current levels (gray) and fixed phenology at current levels (red). Yield impacts were calculated as the ensemble mean of seven climate models, weighted by gridded harvested areas. Box plot indicated median (white line), 25–75th percentiles (box), 5–95th percentiles (whiskers), and mean value (black dot). **c,d**, Spatial distribution of projected relative yield change under both assumptions.

amounts modulate these impacts remains uncertain. Quantifying this relationship is essential for assessing the risk of yield reductions in irrigated crops due to future climate change, especially as water resources become more limited and deficit irrigation, applying less water than full crop-water requirements, may become more likely as a viable adaptation strategy[39]. The Ogallala Aquifer region, where maize production heavily depends on irrigation due to inadequate annual Prcp (ranging from 500 mm in the east to 200 mm in the west; Supplementary Fig. 2), serves as an ideal natural laboratory for investigating the role of irrigation in sustaining yields. This study employed a panel regression model that integrates dynamic irrigation effects to assess future climate-driven changes in maize yield and irrigation requirements.

Recent research has shown that conversion from center pivot irrigation to subsurface irrigation can reduce maize irrigation requirements while maintaining yields[40,41]. Although our analysis did not specifically focus on irrigation methods, most irrigation systems included in the meta-analysis utilized sprinkler irrigation, such as center pivot systems, which is the most widely used in the US[42,43] and generally more efficient than surface (furrow) irrigation[44]. Additionally, due to data limitations regarding specific irrigation amounts during different growth stages, our analysis was constrained to

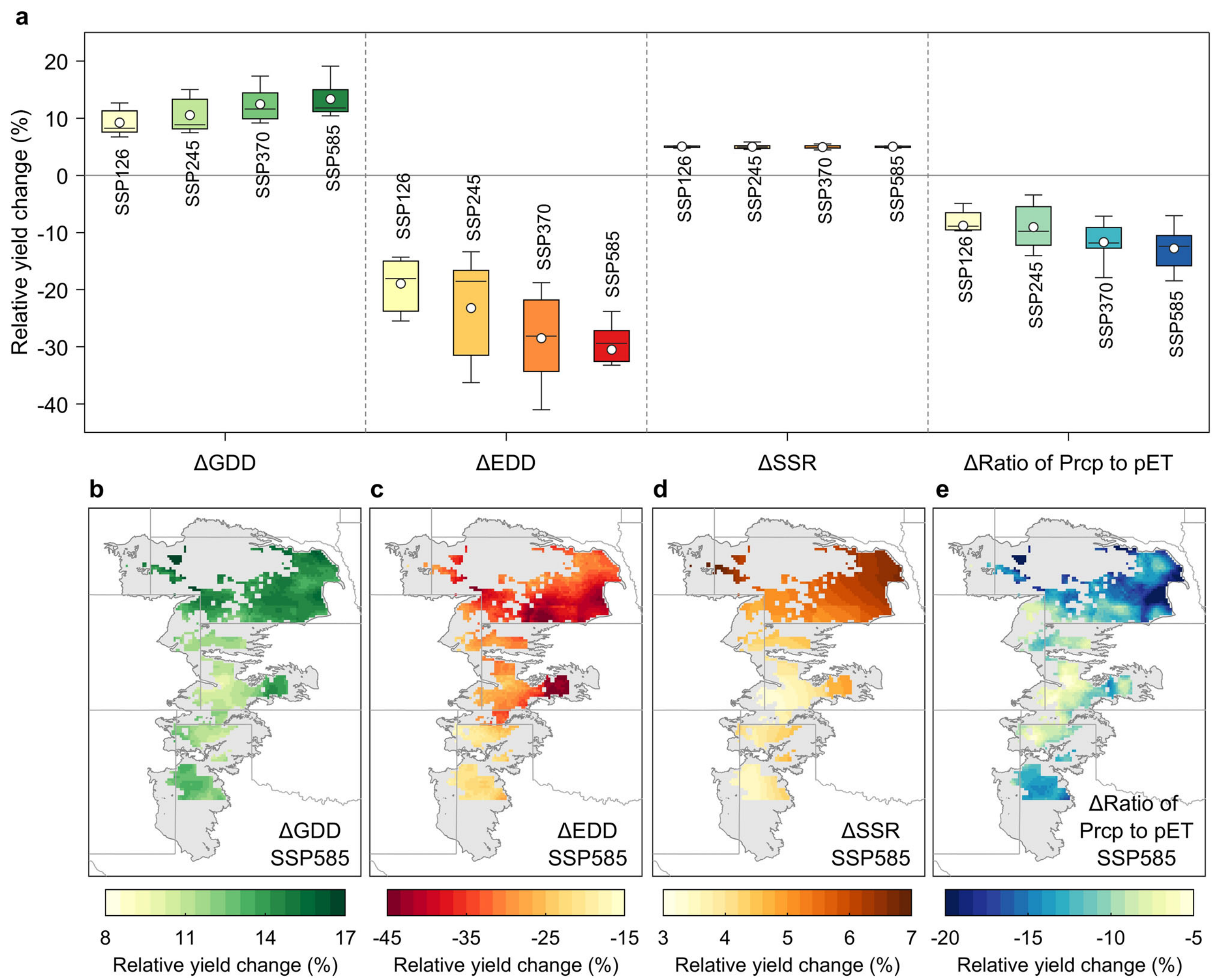

Fig. 4 | Decomposition of climate drivers affecting irrigated maize yield changes for 2050–2059 under SSP126, SSP245, SSP370, and SSP585 scenarios. a Yield change was attributed to specific climate change factors, including changes in growing degree days (ΔGDD), extreme degree days (ΔEDD), solar radiation (ΔSSR), and the ratio of precipitation to potential evapotranspiration (ΔRatio of Prcp to pET). The climate change-induced yield changes were calculated as the ensemble mean of seven climate models, weighted by gridded harvested areas. Box plot indicated median (black line), 25–75th percentiles (box), 5–95th percentiles (whiskers), and mean value (circle). **b–e**, Spatial distribution of climate drivers contributing to yield changes under the SSP585 scenario.

total irrigation amounts throughout the growing season (from planting to maturity). However, these irrigation amounts may be distributed unevenly during the growing season, affecting irrigation efficiency[39]. Thus, improving data on irrigation timing would help to further refine our understanding of how irrigation will influence yield resilience under future climate change scenarios. Despite these limitations, our study provides additional perspective to previous studies on the role of irrigation in mitigating climate impacts.

Theoretically, future maize phenological dates could shift due to changes in climate conditions and management practices. However, in this study, we fixed future planting and maturity dates based on local historical averages. Our primary goal was to evaluate the impact of future climate change on maize yield under historical irrigation levels. To achieve this, we controlled future phenological windows to align with historical benchmarks, providing a practical reference point. This approach allowed us to assess the influences of future climate on maize yield in comparison to historical climate conditions within the same phenological window, consistent with the approach used in previous studies[45,46]. Thus, we did not consider the potential advancement of planting dates, which may increase the risk of exposing maize to early spring frosts, adding uncertainty to our projections. For comparison, we also conducted a "fixed GDD" scenario, assuming that future maize hybrids will maintain the same GDD requirements as current hybrids, implying no adaptation to climate change. Without adaptation, crops may experience accelerated maturation and shortened growth durations due to rising temperature, leading to larger yield losses. Future studies could explore optimal adaptation strategies that combine crop variety selection[28] and phenological adjustments[47] under irrigation to further minimize yield effects.

In summary, our results indicated that irrigation amount plays a critical role in adjusting maize yield responses to water and heat stress. We found each additional 100 mm of irrigation reduced yield sensitivity to heat stress by an average of 7.6%, emphasizing the importance of effective irrigation strategies in enhancing resilience to climate warming. Additionally, many field and experimental site studies have observed the nonlinear yield response to water supply; they typically focus on local conditions. In contrast, our study quantified this relationship at a regional scale, integrating climate and water supply variations to provide actionable insights for optimizing irrigation practices more broadly. By identifying the saturation effect of yield gains, we offer a framework for determining optimal irrigation thresholds tailored to different Prcp zones. This is crucial for improving water use efficiency and developing adaptive irrigation strategies that account for regional climatic variability, ultimately supporting sustainable

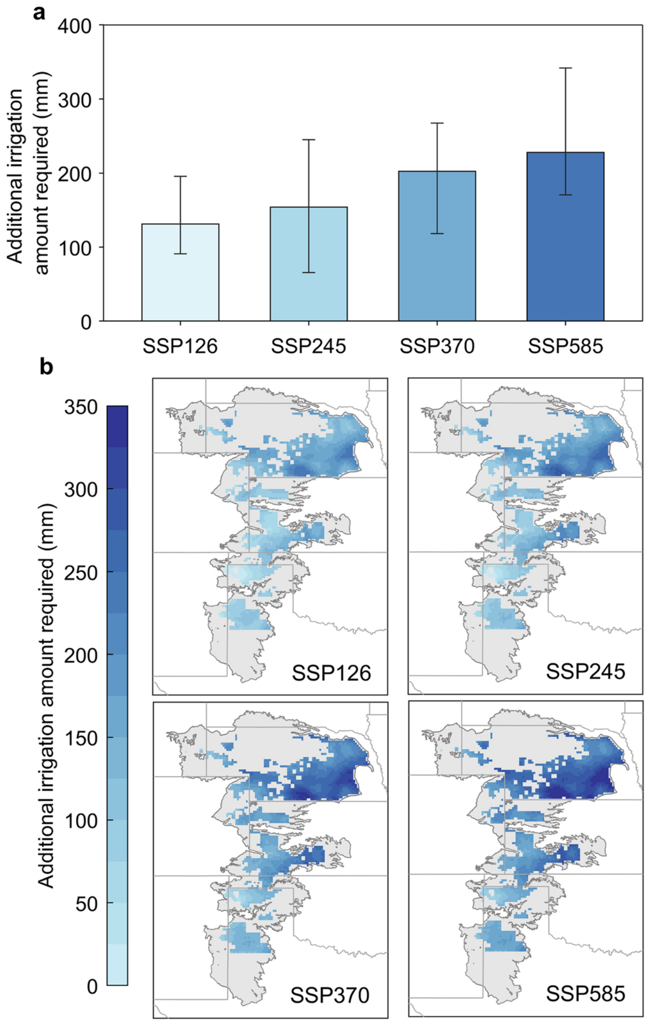

Fig. 5 | Projected irrigation amount needed to offset climate change-induced yield losses in irrigated maize for 2050-2059 under SSP126, SSP245, SSP370, and SSP585 scenarios. a The additional irrigation amount needed to compensate for yield losses due to climate change was calculated as the ensemble mean of seven climate models, with the error bars showing the 2.5–97.5th percentiles. Values were weighted by gridded harvested areas. **b** Spatial distribution of the additional irrigation requirements for each climate scenarios.

water resource management in water-limited crop production regions. Furthermore, we integrated these relationships into projections of future climate impacts on irrigated maize yields and irrigation demand. Projections indicated that, without changes in irrigation levels, maize yields could decline by 20% on average by the 2050s across four climate scenarios, primarily due to increased heat stress. To fully offset these potential losses, an estimated 228 mm of additional irrigation would be necessary under the high-emission scenario (SSP585), implying the challenges of balancing food demand with sustainable water use under a warming climate. While irrigation can help mitigate heat sensitivity in crop yields, the substantial water demand required to offset potential yield declines under future climate scenarios highlights the need for more integrated and efficient strategies. These strategies include targeted irrigation during critical crop growth stages to reduce water use, integrating the relationships between irrigation amounts and climate impacts (heat and drought) into crop models[48–50] to optimize irrigation management, and aligning irrigation practices with broader climate adaptation and water management policies. Additionally, as water availability is likely expected to decrease in arid and semi-arid regions, a combination of efficient irrigation, crop diversification, and the use of drought- and heat-tolerant hybrids will be crucial for enhancing resilience and ensuring long-term sustainability.

Furthermore, the results of this study contribute to the debate about whether the production of maize for grain should be a priority use of Ogallala Aquifer water, particularly in the central and southern areas of the aquifer in Kansas and Texas, where evapotranspiration rates are larger and Prcp is smaller. In these areas, forage production is a priority to support a burgeoning dairy industry and the already large cattle feeding industry. However, maize grain can be brought into the region from the Midwest economically on unit trains, whereas forages for beef and dairy production must be produced more locally due to the cost of transportation. Also, forage growing and irrigation seasons are both shorter, and irrigation demands are smaller than those necessary for maize grain production. Given the declining aquifer, which means that increased irrigation is not a realistic adaptation to climate change without severe reductions in area devoted to maize grain, conversion of maize grain areas to forage production is likely.

Methods

Literature search

A comprehensive search for peer-reviewed publications on the effect of irrigation on maize yield in the U.S. was conducted using Google Scholar and Web of Science. Search terms included "corn," "maize," "deficit (or limited) irrigation," and "water use." Publications were screened based on the following criteria: (1) studies focusing on field-based maize conducted in the Ogallala Aquifer states (Fig. 1) during the period of 1986–2020, and (2) studies providing data on planting and harvest (or maturity) dates, plant population density (plants ha^{-1}), nitrogen application rate (kg ha^{-1}), maize yield (t ha^{-1}; adjusted to 15.5% standardized moisture content), and irrigation amounts (mm) during the growing season. This screening process identified 33 relevant publications, yielding 707 observations across 87 site-years (Fig. 1). The complete reference list of publications is given in Supplementary Table 1.

Climate data

To characterize historical weather conditions, we extracted daily maximum temperature (Tx) and minimum temperature (Tn), and Prcp from the Global Historical Climatology Network-daily[51]. Daily SSR data were obtained from the Prediction of Worldwide Energy Resources, National Aeronautics and Space Administration (NASA/POWER). Additionally, daily pET was taken from the gridded meteorological dataset[52]. We then interpolated climatic data with a Delaunay Triangulation[53] to field sites to approximate the daily weather experienced by the crop.

Estimating effects of irrigation on maize yield

We developed a linear mixed-effects model to quantify the influence of climate variables on maize yield, with a focus on how irrigation mitigates heat and water stress. All climate variables were calculated over the maize growing season (from planting to maturity). For cases where maturity dates were unavailable, we estimated maturity dates as four weeks prior to the reported harvest date[54]. The model is specified as:

$$
\begin{aligned}
Y_{l,t,i} = {} & \alpha_t + \beta_1 GDD_{l,t,i} + \beta_2 EDD_{l,t,i} + \beta_3 SSR_{l,t,i} + \beta_4 \frac{Prcp_{l,t,i} + Irr_{l,t,i}}{pET_{l,t,i}} \\
& + \beta_5 \left(\frac{Prcp_{l,t,i} + Irr_{l,t,i}}{pET_{l,t,i}} \right)^2 + \beta_6 Irr_{l,t,i} \times EDD_{l,t,i} + \gamma_1 N_{l,t,i} + \gamma_2 N_{l,t,i}{}^2 \\
& + \gamma_3 Pop_{l,t,i} + \gamma_4 Pop_{l,t,i}{}^2 + \gamma_5 Sand_l + \gamma_6 Silt_l + \varepsilon_{l,t,i}
\end{aligned}
\tag{1}
$$

where $Y_{l,t,i}$ (t ha^{-1}) is maize yield for site l, year t, and observation i. α_t represents the random intercept effect for years, commonly used to control the influence of unobserved factors, such as advancements of maize hybrids over time. α_t is estimated using a categorical variable for years. *GDD* (°C days) denotes GDD between 8 and 30 °C, and *EDD* (°C days) represents

EDD above 30 °C[34,35], both calculated using hourly temperature simulated from Tx and Tn[55]. *SSR* (MJ m^{-2}) is accumulated solar radiation.

To characterize water stress, we calculated the ratio of $\frac{Prcp+Irr}{pET}$, where *Prcp* (mm) is the accumulated precipitation, *Irr* (mm) is the accumulated irrigation amounts, and *pET* (mm) is the accumulated pET during the maize growing season. We included the interaction term ($Irr \times EDD$) in our model, allowing us to quantify the moderating effects of irrigation on yield sensitivity to EDD as $\frac{\partial Y}{\partial EDD} = \beta_2 + \beta_6 Irr$. Note that we interpreted the effect of the interaction term ($Irr \times EDD$) with respect to *EDD*, as our objective is to quantify how irrigation mitigates the impact of heat stress on crop yields, rather than how heat stress influences the efficiency of irrigation. We also tested the statistical significance of this interaction term using a simulated likelihood ratio test[56], suggesting that incorporating this term significantly (p value < 0.05) enhanced the model's performance compared to the model that excluded it. All variance inflation factors values for climate predictors are below 7, confirming that multicollinearity is not a concern in our model.

To capture the effects of main management practices on maize yield, we included nitrogen application rate (*N*) and plant population density (*Pop*) in the model. We used quadratic terms of these two variables to account for the potential nonlinear influence on yields[57,58]. To capture site-specific soil influences, we directly incorporated key soil properties rather than using site-fixed effects, which can restrict predictions to known sites. Specifically, we used layer-weighted averages for soil texture (sand and silt proportions) in the top 100 cm of soil, derived from the nearest 30-m grid cell in the POLARIS soil dataset[59]. This dataset, developed based on the Soil Survey Geographic Database (SSURGO) and the State Soil Geographic Database (STASGO2), provides high-resolution soil characteristics that effectively represent local conditions. As the sum of sand, silt, and clay proportions equals to 1, we only included the proportion of sand and silt in the model to prevent multicollinearity. By including soil texture, the model captures important site-level variation, allowing for broader spatial predictions across various regions.

Additionally, the β terms represent the set of coefficients associated with climatic variables influencing maize yields. Specifically, β_1 and β_2 capture the nonlinear effects of temperature on yields (unit: t ha^{-1} [°C days]$^{-1}$); β_3 quantifies the effect of *SSR* on yields (unit: t ha^{-1} [MJ m^{-2}]$^{-1}$); β_4 and β_5 indicate the nonlinear effects of water conditions on yields (unit: t ha^{-1} [mm mm^{-1}]$^{-1}$); β_6 represents the effect of irrigation in alleviating heat stress (unit: t ha^{-1} [mm °C days]$^{-1}$). γ represents the coefficients of management practices (γ_1 to γ_4) and soil characteristics (γ_5 and γ_6). Specifically, γ_1 and γ_2 capture the potential nonlinear effects of *N* on yields (unit: t ha^{-1} [kg N ha^{-1}]$^{-1}$); γ_3 and γ_4 represent the potential nonlinear effects of plant population density on yields (unit: t ha^{-1} [plants ha^{-1}]$^{-1}$); γ_5 and γ_6 describe the effects of soil sand and clay content, respectively (unit: t ha^{-1} percentage^{-1}).

Projected climate-driven changes in irrigated maize yield

We projected climate change-driven yield changes for irrigated maize in the Ogallala Aquifer region, focusing on grid cells with harvested areas more than 300 hectares (Fig. 1)[60]. The average climate condition during the 2010s (2010–2019, excluding 2012 due to severe drought and low yields[61]) was used as a current climate baseline. To estimate irrigation needs to achieve current maize yields in farmers' fields, we used three additional datasets during the 2010s: (1) state-level phenology (planting and maturity dates) estimated[62,63] based on the US Department of Agriculture, National Agricultural Statistics Service (USDA-NASS) (Supplementary Fig. 4); (2) management practices (N fertilizer and plant population density) for irrigated maize field trials from online publicized state's Maize Performance Test Reports (Supplementary Table 3); and (3) agricultural district-level irrigated maize yield data from USDA-NASS (Supplementary Fig. 1), which offered broader spatial coverage than county-level yield data. These data typically represent current management practices and maize yield levels in the Ogallala Aquifer region.

To estimate the average irrigation amounts required to achieve the observed average yields (Supplementary Fig. 1) under current management practices across the Ogallala Aquifer (Fig. 3a), we first interpolated the 2010s climate data to the grid cells and calculated the climate variables during the growing season based on the state-level phenology. We then calculated the average N fertilizer rate (234 kg ha^{-1}) and plant population density (75,191 plants ha^{-1}) based on the public dataset of management practices in irrigated maize fields across our study domain during the 2010s (Supplementary Table 3). These management values, characterizing current farmers' practices, were incorporated into our panel regression model (Eq. 1) to estimate irrigation amounts under historical climate conditions. These baseline irrigation estimates were then used to project climate change-driven yield variation for the 2050s (2050−2059) relative to the 2010s. Projections were conducted for four SSPs (SSPs: SSP126, SSP245, SSP370, and SSP585) using climate data from seven global climate models (GCMs; Supplementary Table 4) provided by the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)[64]. This dataset provides bias-corrected and downscaled climate change projections suitable for evaluating climate change impacts.

To project climate-driven yield changes, we considered two scenarios: (1) fixing future GDD at the 2010s levels, while recalculating future phenology (Supplementary Fig. 5a), and (2) holding phenology fixed at the 2010s levels, while allowing GDD to vary (Supplementary Fig. 5b). The "fixed phenology" scenario maintains phenological windows consistent with historical benchmarks. This approach allows us to isolate the effects of future climate change by removing the influences of shifts in phenological timing, enabling a direct comparison of future climate impacts against historical conditions. This assumes that farmers could adapt to climate warming by selecting hybrids with longer GDD requirements to maintain the historical length of the growing season. In contrast, the "fixed GDD" scenario assumes that farmers continue to use current hybrids with the same GDD requirements, representing a non-adaptative baseline. This estimation captures the direct effects of climate change on crop yield and its indirect effect through changes in the length of growing season.

To assess the impacts of climate change on maize yield, we first projected irrigated maize yields for the 2050s under four SSP scenarios using our fitted regression models (Eq. 1). To isolate the effects of climate change, we used future climate variables in the models while management practices (irrigation amounts, *N* fertilizer rate, and plant population density) were held constant at historical average levels (2010–2019). We then calculated the yield changes relative to the historical average yield. We further quantified the contributions of changes in specific climate variables between the 2050s and the 2010s to yield changes (ΔY) using our model (f):

$$\Delta Y = f(Climate_2) - f(Climate_1) \tag{2}$$

Here, $Climate_1$ and $Climate_2$ refer to the sets of climate variables used in our model (Eq. 1), averaged over the 2010s and 2050s, respectively. For each grid, the ΔY is explained by the changes in four climate components:

$$\Delta Y_{GDD} = \beta_1 (GDD_2 - GDD_1) \tag{3}$$

$$\Delta Y_{EDD} = \beta_2 (EDD_2 - EDD_1) + \beta_6 Irr \times (EDD_2 - EDD_1) \tag{4}$$

$$\Delta Y_{SSR} = \beta_3 (SSR_2 - SSR_1) \tag{5}$$

$$\Delta Y_{\frac{Prcp}{pET}} = \beta_4 \left(\frac{Prcp_2 + Irr_1}{pET_2} - \frac{Prcp_1 + Irr_1}{pET_1} \right) + \beta_5 \left(\left(\frac{Prcp_2 + Irr_1}{pET_2} \right)^2 - \left(\frac{Prcp_1 + Irr_1}{pET_1} \right)^2 \right) \tag{6}$$

where the subscripts "1" and "2" denote the averages for the reference period (the 2010s) and the future period (the 2050s), respectively.

Data availability

The data sources for the meta-analysis are listed in Supplementary Table 1. Other data sources used in this study are provided in Supplementary

Tables 3 and 5. The data used to display main figures are shown at https://figshare.com/s/52b0c22495a43dc6d175.

Code availability

The code used to generate main figures in this study is available through a public repository at https://figshare.com/s/52b0c22495a43dc6d175.

Received: 17 January 2025; Accepted: 9 June 2025;
Published online: 20 June 2025

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Acknowledgements

This study was supported by the U.S. National Science Foundation projects (2345039 and 2420405) (X.L) and USDA Agricultural Research Service (A22-0103-001) (X.L). Contribution no. 25-138-J is from the Kansas Agricultural Experiment Station. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. The USDA is an equal opportunity provider and employer.

Author contributions

X.L., G.B., and L.Z. designed and coordinated the research, conducted the analysis, and wrote the initial manuscript draft. L.Z. and H.Z. collected all the data needed. S.R.E. and X.L. contributed to discussing the methodology and the results. S.R.E., P.D.C., Q.X., G.M., R.D., H.Z., and N.W. interpreted the results, advised on presentation of the main findings, and contributed to the writing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02459-y.

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Peer review information *Communications Earth and Environment* thanks Zewei Ma, Mahmoud Suliman and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editor: Aliénor Lavergne. [A peer review file is available].