Environmental Research Communications

OPEN ACCESS

RECEIVED
30 April 2024

REVISED
26 June 2024

ACCEPTED FOR PUBLICATION
16 July 2024

PUBLISHED
24 July 2024

LETTER

Sensitivity changes of US maize yields to extreme heat through timely precipitation patterns

Haidong Zhao[1], **Lina Zhang**[1], **Nenghan Wan**[1], **Tom J Avenson**[2], **Stephen M Welch**[1] **and Xiaomao Lin**[1]

[1] Department of Agronomy, Kansas State University, 2004 Throckmorton Hall, Plant Sciences Center, Manhattan, KS 66506, United States of America

[2] Vindara Inc., Orlando, FL 32812, United States of America

E-mail: xlin@ksu.edu

Keywords: fraction of timely precipitation, extreme heat, maize yields, mitigation, US Corn Belt

Supplementary material for this article is available online

Abstract

Warm temperatures due to increases of greenhouse gas emissions have changed temperature distribution patterns especially for their extremes, which negatively affect crop yields. However, the assessment of these negative impacts remains unclear when surface precipitation patterns are shifted. Using a statistical model along with 23,944 county-year maize-yield data during 1981–2020 in the US Corn Belt, we found that the occurrence of timely precipitation reduced the sensitivity of maize yields to extreme heat by an average of 20% during the growing season with variations across phenological periods. Spatially across the US corn belt, maize in the northern region exhibited more significant benefits from timely precipitation compared to the southern region, despite the pronounced negative effects of extreme heat on yields in cooler regions. This study underscores the necessity of incorporating timely precipitation as a pivotal factor in estimating heat effects under evolving climates, offering valuable insights into complex climate-related challenges.

1. Introduction

Delving into the intricate interplay of various climate factors and their influences on food production (Godfray *et al* 2010) is crucial for understanding how crops adapt to climate change. Extensive literature, referencing various experimental (Zhao *et al* 2017), observational (Lobell *et al* 2011), and modeling approaches (Asseng *et al* 2015), underscores the adverse effects of extreme heat on crop yields (Barlow *et al* 2015). The escalation of such heat events is evident globally and is projected to persist in the coming decades (Siebert and Ewert 2014), regardless of shifts in greenhouse-gas emission policies (Van Aalst 2006).

Against this backdrop, anticipated changes to the Earth's hydrological cycle are expected, resulting in heterogeneous effects on precipitation across different time and space scales. For example, the likelihood of daily precipitation is expected to change during a heatwave period (Mahto and Mishra 2024) followed the Clausius–Clapeyron theory (Lu 2007, Koutsoyiannis 2012). The occurrence of precipitation under extreme heat days (hereafter referred to as timely precipitation) could provide potentials to alter the impact of heatwaves on crop yields through physical and physiological processes, introducing nuanced dynamics into the understanding of climate-crop interactions. This influence couples through at least two fundamental aspects, including water supply and atmospheric thermal dynamics in near surface boundary layers. High temperatures increase the potential of crop water demand and decrease soil water availability to plants via enhanced evapotranspiration (Sadok *et al* 2021), leading to worse water stress for crop growth and lower yields (Lipiec *et al* 2013, Zhao *et al* 2022). Precipitation serves as a proxy for soil moisture in rainfed cropping systems and can alter extreme heat–yield relationships in multiple ways. Besides its role in supplying water to the soil, timely precipitation can also cool leaf temperature as water drops evaporate (Trenberth and Shea 2005, Mueller and Seneviratne 2012). Indeed, the impacts of extreme heat on crop yields are exacerbated under drought conditions (Lobell *et al* 2011, Zhao *et al* 2022), while they are alleviated when accompanied by timely irrigation (Lobell *et al* 2008). However, the role of timely precipitation in modulating the impacts of extreme heat on crop yields has received limited empirical study, hindering our ability to better understand and possibly manage cropping systems under a changing climate.

Previous studies have indicated greater precipitation could alleviate the negative effects of extreme high temperatures (Schlenker and Roberts 2009, Leng 2019, Luan *et al* 2021) on crop yields when considering total seasonal (or monthly) precipitation amounts. However, this approach does not capture the influence of fractions of timely precipitation (FTP) during periods of heat stress on crop yields.

To explore FTP impacts, we focus on maize in the US Corn Belt, a crop that is both highly productive and strongly influenced by temperature (Butler and Huybers 2013). The FTP is defined as the fraction of days with an intersection between extreme heat days and daily precipitation $\geqslant 9.5$ mm to total extreme heat days (Zhu *et al* 2022) (see Data and Methods). The main objective of our study is to empirically estimate how yield sensitivity to heat stress can be modified by FTP during specific phenological periods. To achieve this, we constructed a linear mixed-effects model attributing interannual variability in yields to multiple environmental factors, including growing degree days, extreme degree days, precipitation, and FTP during three phenological periods of maize growth (planting to 14 days before silking, around silking ($\pm$14 days), and 14 days after silking to maturity).

2. Data and methods

2.1. Maize and climate data

Rainfed maize yields at the county-level and phenology dates at the state-level, including planting (PT), silking (SK), and harvest (HV), are retrieved from reports of the United States Department of Agriculture's National Agricultural Statistical Service (USDA-NASS) during 1981–2020 across rainfed US maize production states including Iowa, Illinois, Indiana, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. One county was selected when available yield data is longer than 35 years; lastly, we selected 612 counties for this study. Because the USDA-NASS Crop Progress Report is released on a weekly basis as a progress percentage, we interpolated the weekly crop progress into daily data using the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) approach (Fritsch and Carlson 1980, Sacks and Kucharik 2011). We then calculated PT, SK, and HV and defined them as dates when the crop's progress toward each stage reached 50% across the state. We then derived maturity date (MT) which is defined as 4 weeks before HV (Tollenaar *et al* 2017). In total, the database we used included 23,944 county-year samples. We used county-level daily precipitation (mm), daily minimum temperature (T_{min}, °C), and daily maximum temperature (T_{max}, °C) from NOAA's nClimGrid-Daily (Durre *et al* 2022), which was developed based on observations in the Global Historical Climatology Network Daily (GHCNd) dataset (Menne *et al* 2012).

2.2. Statistical model

We calculated the cumulative exposure to growing degree days (GDD, °C days, equation (1)) between the base and optimum growth temperature thresholds, and extreme degree days (EDD, °C days, equation (2)) above the optimum growing temperature threshold at specific phenological periods. Both GDD and EDD calculations were based on hourly temperatures (T_h) obtained from daily temperatures (Cesaraccio *et al* 2001), which combines daily T_{min} and T_{max}. The phenological periods were partitioned as planting to 14 days before silking, around silking ($\pm$14 days), and 14 days after silking to maturity (Ortiz-Bobea and Just 2013, Tollenaar *et al* 2017). GDD and EDD play the crucial roles in determining maize ears, kernel numbers, kernel weight, and consequently, overall yields.

$$GDD = \sum_{h=1}^{H} DD_h;\ DD_h = \begin{cases} 0 & T_h < T_{base} \\ \dfrac{T_h - T_{base}}{24} & T_{base} \leqslant T_h \leqslant T_{opt} \\ \dfrac{T_{opt} - T_{base}}{24} & T_h > T_{opt} \end{cases} \quad (1)$$

$$EDD = \sum_{h=1}^{H} DD_h;\ DD_h \begin{cases} 0 & T_h \leqslant T_{opt} \\ \dfrac{T_h - T_{opt}}{24} & T_h > T_{opt} \end{cases} \quad (2)$$

where T_{base} and T_{opt} are the base (10 °C) and optimum (30 °C) growing temperature thresholds for the US Corn Belt, which are common thresholds for the growth and development in maize (Schlenker and Roberts 2009, Sacks and Kucharik 2011). DD_h refers to hourly growing degree days. H is total hours during the specific phenological period.

We then calculated FTP as a ratio of days with both daily EDD > 0 and daily precipitation amount $\geqslant 9.5$ mm to days with daily EDD > 0, as follows:

$$FTP = \frac{Days\ with\ EDD > 0 \cap Days\ with\ Prcp \geqslant 9.5}{Days\ with\ EDD > 0} \tag{3}$$

Here we defined 9.5 mm as a precipitation threshold for effective precipitation to alleviate heat stress. This threshold was determined based on optimal model performance (equation (4)), with the smallest Akaike Information Criterion (figure S1). The AIC is a measure used in statistics to evaluate and compare the goodness-of-fit of different mathematical models; when comparing multiple models, the one with the lowest AIC value is generally preferred (Akaike 2011). We systematically set up threshold windows for precipitation, ranging from 5 mm to 15 mm with a step size of 0.5 mm. For each threshold within this range, model fitting was conducted to assess model performance. This process allows us to identify the threshold that yields the best model performance. The selection of threshold in precipitation (9.5 mm) also aligns with water demand of maize during the summer in the US Corn Belt (Sharratt *et al* 2001). FTP = 0 indicates the absence of timely precipitation when maize is exposed to heat stress, while FTP = 1 represents the complete alignment of all extreme heat events with timely precipitation. The '$\bigcap$' indicates intersection of both extreme heat and precipitation events.

We used a linear mixed-effects model to examine the impacts of climate indices on maize yields and whether $\frac{\partial Y}{\partial EDD}$ is regulated by FTP as,

$$Y_{i,t} = \sum_{p=1}^{3} (\alpha_p GDD_{i,t,p} + \beta_{p,1} Prcp_{i,t,p} + \beta_{p,2} Prcp_{i,t,p}^2 + \gamma_p EDD_{i,t,p} + \delta_p EDD_{i,t,p} \times FTP_{i,t,p}) + \vartheta_{i,1} t + \vartheta_{i,2} t^2 + C_i + \varepsilon_{i,t} \tag{4}$$

where Y refers to yields (t ha^{-1}) in county i and year t. α, β, γ, and δ are the sensitivities of maize yields to weather variables during the specific phenological periods 'p.' ϑ refers to yield trends over time, which mainly results from advancement in agricultural management and breeding advances for a specific county i. We also added the control variable of a county-specific vector (C_i) to account for time-invariant spatial heterogeneity. The $\varepsilon_{i,t}$ refers to random error terms. The residuals of model follow the normal distribution (figure S2).

2.3. Modulation of FTP on the extreme heat impacts

The EDD effects during specific phenological periods were calculated as the first derivative of maize yields with respect to the EDD ($\frac{\partial Y}{\partial EDD_p}$), expressed as a linear function of FTP,

$$\frac{\partial Y}{\partial EDD_p} = \gamma_p + \delta_p \times FTP_p \tag{5}$$

Then, the mitigating percent (MP, %) of average FTP on the sensitivity of maize yields to EDD for each phenological period across the US Corn Belt was calculated as,

$$MP_{i,p} = \frac{\gamma_p + \delta_p \times \overline{FTP_{i,p}}}{\gamma_p} \times 100 \tag{6}$$

Similarly, total mitigating percent of average FTP on the sensitivity of maize yields to EDD across the whole growing season was then calculated as,

$$MP_i = \sum_{p=1}^{3} \frac{\gamma_p + \delta_p \times \overline{FTP_{i,p}}}{\gamma_p} \times 100 \tag{7}$$

where $\overline{FTP}$ refers to average FTP across years (1981–2020) for each county.

3. Results

Part of the challenge in investigating the mitigation effects of timely precipitation on heat stress lies in variable distributions in daily precipitation during heat periods (FTP) within a given year, which cannot be directly captured by long-term rainfall totals. Under the identical EDD and total precipitation, FTP for two different years in the same locations may be different. For example, there were consistent EDD and total precipitation between 1982 and 1989 years in Pulaski, Illinois, but the FTP was two times higher in 1982 than in 1989 (figures 1(a) and (b)). Before analyzing the effects of FTP, we initially examined changes in maize yields across ten FTP bins over the past four decades and found that improvements in yields correlated with increased FTP (figure 1(c)).

Figure 2 shows the spatial distribution of FTP during specific phenological periods across the US Corn Belt from 1981 to 2020. The distribution of FTP varied substantially over regions, with the northern region experiencing more frequent FTP than the southern region, especially in the P2 period with an average of 13%

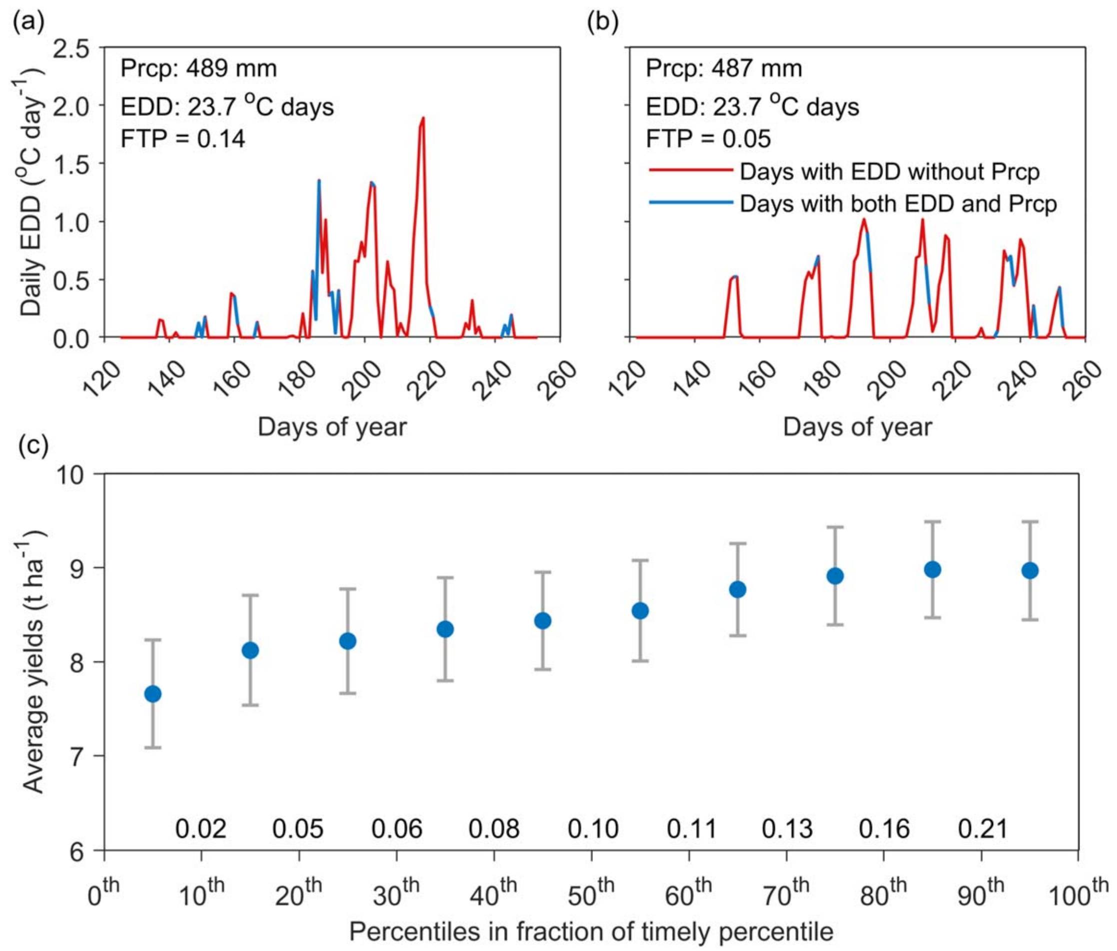

Figure 1. Fraction of timely precipitation (FTP) coinciding with extreme degree days (EDD) during the maize growing season and corresponding to impacts on maize yields in the US Corn Belt. (a), (b) An illustration of daily EDD (red) accompanied with timely precipitation (blue) in 1982 (a) and in 1989 (b) for Pulaski county in Illinois. (c) Average maize yields for the percentile bins of FTP. The bars show the 95% confidence intervals of yields and the solid circles denote the average yields. The numbers above the x-axis indicate the value of FTP at the specific percentiles. Averaged yields for each FTP bin were determined through the following steps: (1) calculating thresholds of each bin based on all 23,944 county-year FTPs samples (data were shown in methods); (2) partitioning all county-level yields of each year into ten bins based on FTP percentile, which isolates impact of technological change on yields; (3) calculating average yields across years for each TPF percentile.

(figure 2). We then examined the influence of FTP on the sensitivity of maize yields to EDD by incorporating an interaction effect between FTP and EDD into a linear mixed-effects model. Without FTP effects, one-unit increase in EDD during P1, P2, and P3 periods led to yield declines of 0.06 t ha^{-1}, 0.09 t ha^{-1}, and 0.05 t ha^{-1} in the US Corn Belt, respectively (figure 3(a) and table S1), with the highest sensitivity observed in the P2 period (figure 3(a)). However, as FTP increases, the sensitivity to EDD significantly weakens for each period (figure 3(a)), highlighting the beneficial role of timely precipitation in mitigating heat effects. Considering the historical mean FTP for specific periods across the US Corn Belt over 1981–2020, we found that FTP alleviates 20% of sensitivity in maize yields to extreme heat throughout the growing season. Notably, the most significant mitigation, a 30% decline, occurred during the P1 period, followed by a 19% in the P2 period, and a 9% reduction in the P3 period (figure 3(a)). Additionally, the positive impact of an increase in growing degree days (GDD) on maize yields was notable for each growth period, with a particularly pronounced effect during the P3 period. One-unit increase in GDD led to a significant yield enhancement of 0.005 t ha^{-1} (figure 3(b) and table S1), consistent with previous studies (Butler *et al* 2018). Figure 3(c) displays the nonlinear relationship between precipitation and maize yields.

We partitioned our data to south and north regions based on latitude boundary (42°N) and conducted separate re-analyses for each dataset. We found that, in the absence of FTP, the yield loss from one-unit increase in EDD during each growth period is larger in northern region compared to southern region (figure 4), which is consistent with prior research that indicated greater sensitivity of maize yields to high temperatures in the US cool region compared to the warm region (Butler and Huybers 2013). Specifically, one-unit increase in EDD decreased yields by 0.05, 0.08, and 0.05 t ha^{-1} in southern region during P1, P2, and P3 periods, respectively. However, the yield loss resulting from one unit change in EDD increased to 0.07, 0.09, and 0.07 t ha^{-1} in

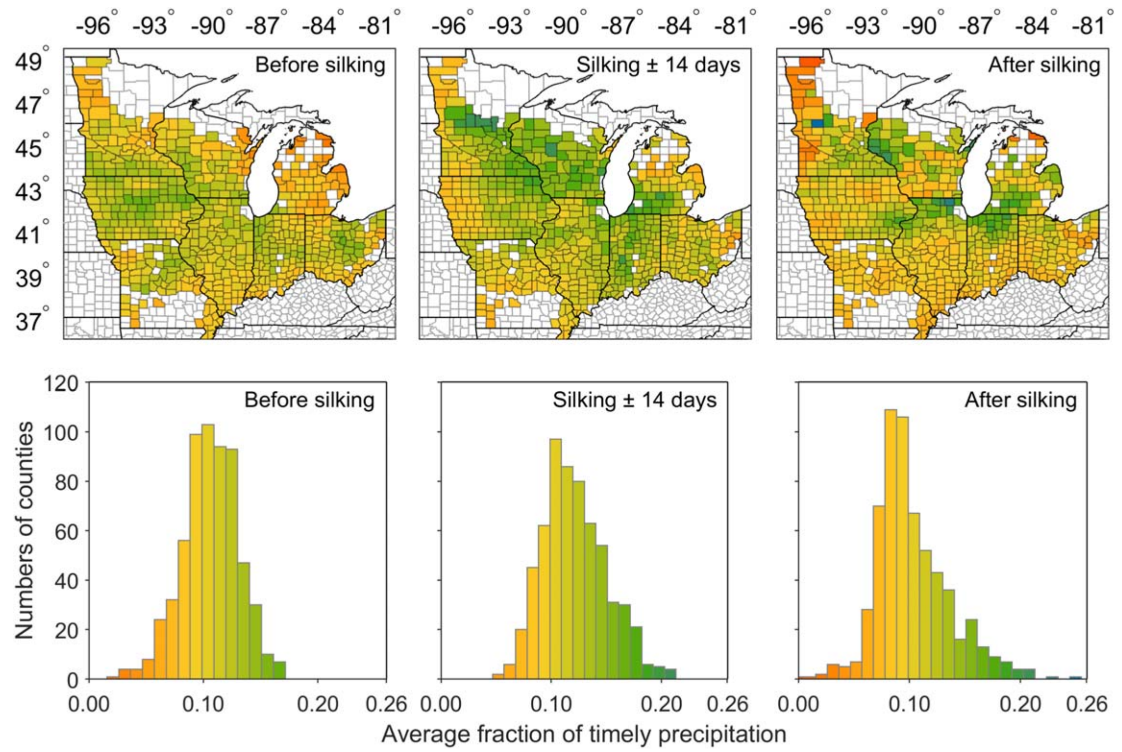

Figure 2. The spatial distribution of county-level average fraction of timely precipitation (1981–2020) at specific phenological periods throughout the maize growing season. The shading in each map corresponds to shading of the bins in the histogram.

northern region among three phenological periods. Furthermore, our analysis showed the mitigating effect of FTP to EDD sensitivity across both the northern and southern regions throughout the entire growing season (figure 4). It is noteworthy that in the northern region, the advantages derived from one unit of timely precipitation were more pronounced compared to the southern region (figure 4). On average, FTP alleviates sensitivity of maize yields to extreme heat by 25.2% across growing season in northern region, which is 6.9% higher than that in southern region (figure 4).

Finally, we assessed the spatial heterogeneity in historical average mitigating effects of FTP on the sensitivity of maize yields to EDD during specific phenological periods across the US Corn Belt from 1981 to 2020 (figure 5). This assessment incorporated the spatial distribution of FTP (figure 2) and the regression results (figure 3(a)) (see Data and Methods). Spatially, the mitigation of FTP on the sensitivity to EDD is greater in the northern region (figure 5), which is attributed to higher exposure to FTP over historical periods (figure 2). The percentage of FTP mitigation effects was most prominent during the P1 period, averaging 30% and ranging from 7.3% to 48.8% (figure 3(a) and figure 5). This finding can be attributed to two key factors. Firstly, the sensitivity to EDD was weaker for the P1 period compared to the P2 period (figure 3(a)), indicating that FTP can exert a more substantial mitigation effect in the context of a weaker sensitivity. Secondly, the yield benefit resulting from the mitigation effect of an additional unit of FTP on EDD sensitivity was higher for the P1 period than other periods (table S1). When considering all growth periods, the occurrence of FTP reduced the sensitivity of maize yields to extreme heat by an average of 20%, ranging from 9.5% to 29.3% (figure 5). This result underscores the importance of accounting for timely precipitation when estimating heat effects in warmer climates.

4. Discussion

Our study demonstrated that the sensitivity of maize yields to extreme degree days (EDD) differs across various growth stages, with the flowering period (P2) being the most adversely affected (figure 3(a)). This result aligns with previous findings (Ortiz-Bobea and Just 2013, Deryng *et al* 2014, Wang *et al* 2021), indicating that the detrimental impact of heat around silking stems from reduced pollen shedding, influencing kernel numbers (Bolaños and Edmeades 1996, Borrás and Vitantonio-Mazzini 2018) and net photosynthetic rates (Crafts-Brandner and Salvucci 2002). Specifically, previous studies have denoted that pre-silking high temperatures reduce the number of kernel as a result of the disturbed flowering pattern (Cicchino *et al* 2010, Lizaso *et al* 2018),

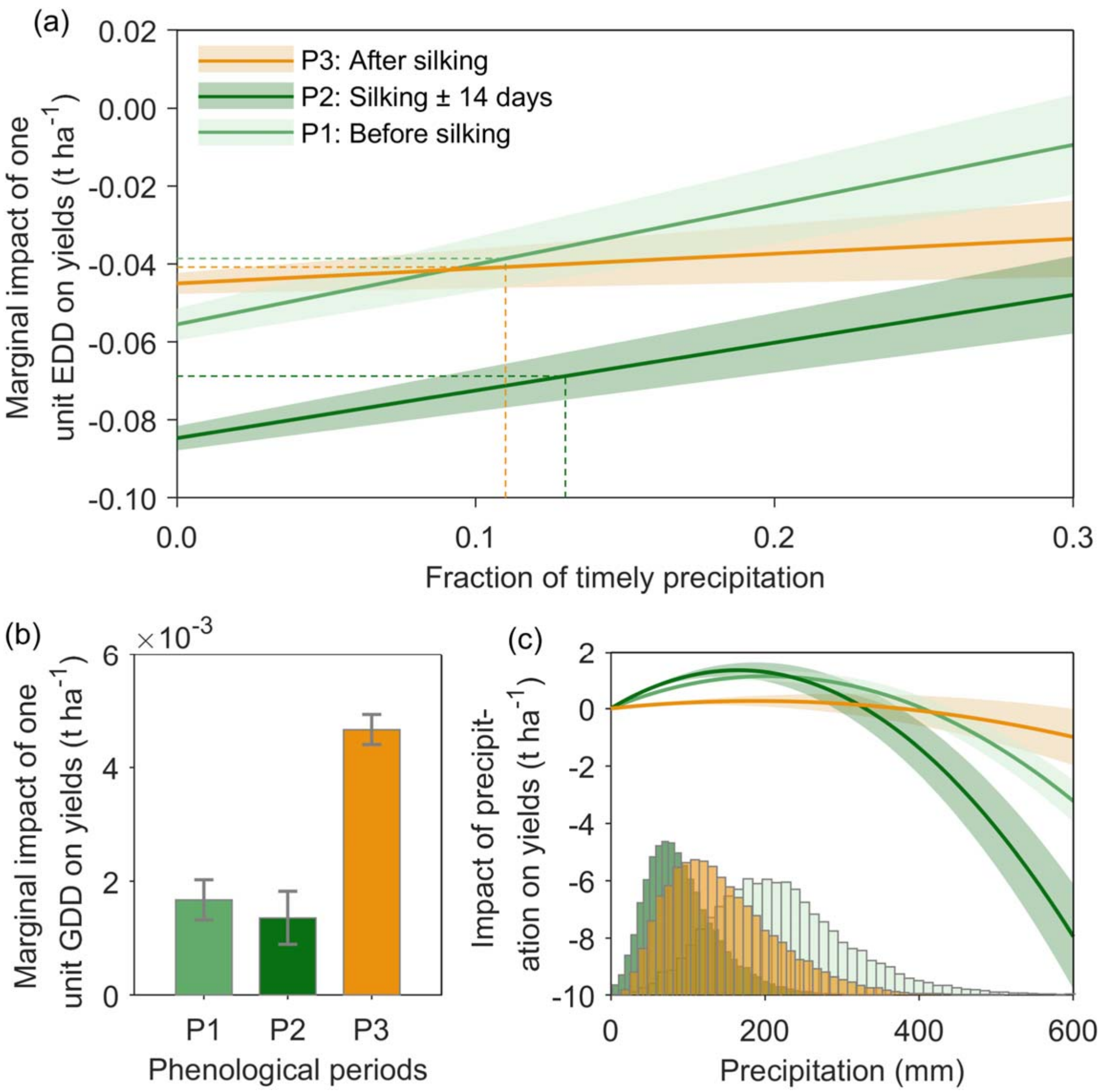

Figure 3. Impacts of temperature and precipitation on maize yields at specific phenological periods. (a) Marginal impact of extreme degree days (EDD) on maize yields as a function of fraction of timely precipitation (FTP) based on interaction term between EDD and FTP. (b) Marginal impact of one unit growing degree days (GDD) on maize yields. (c) Nonlinear impacts of precipitation on maize yields (curve); histograms show distribution of precipitation. Shaded areas (a), (c) and error bars (b) show the 95% confidence interval.

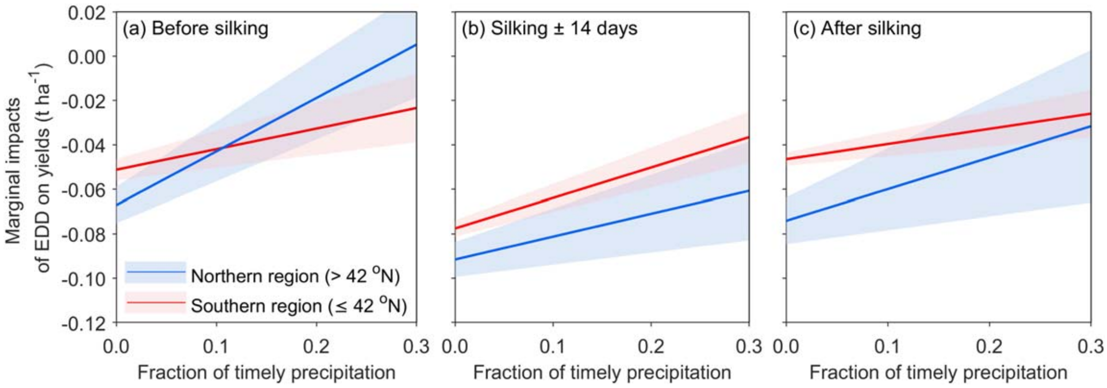

Figure 4. The marginal impact of extreme degree days (EDD) on regional maize yields as a function of the fraction of timely precipitation during specific phenological periods. Blue and red colors represent the northern and southern regions, respectively. The shaded area shows the 95% confidence interval. Notes: Regions are partitioned by latitude (⩽ 42 °N for southern region and > 42 °N for northern region). The model (equation (4) in Data and Methods) was re-run separately for each region.

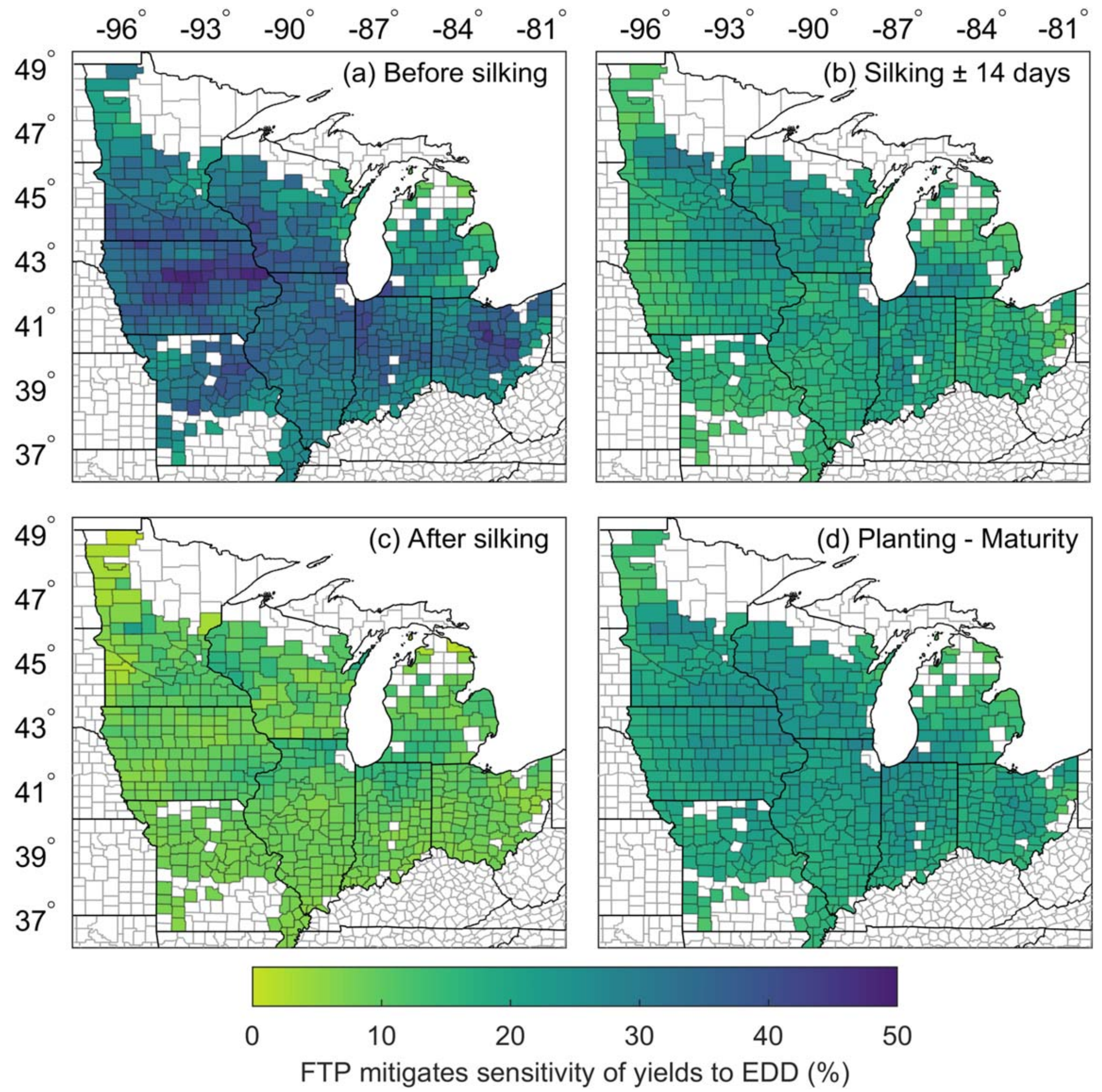

Figure 5. Spatial distribution in mitigation of average fraction of timely precipitation (FTP) on sensitivity of maize yields to extreme degree days in the US Corn Belt from 1981 to 2020.

reduced both pollen shedding number and pollen viability (Wang *et al* 2019), whereas post-silking high temperature resulted in more detrimental effects on kernel formation. Even though many studies have estimated the impact of heat on maize yields (Schlenker and Roberts 2009, Lobell *et al* 2011), they have typically overlooked the spatial variation in sensitivity to heat due to factors of potential adaptation (Butler and Huybers 2013, 2015). To consider the regional adaptation, we divided the study domain into northern (cooler) and southern (warmer) regions based on latitude boundary (42°N) and ran separate regression model for each region. This approach allows for distinct effects of EDD on maize yields in these two regions. The resulting coefficients indicate that northern region demonstrates higher sensitive to heat compared to southern regions (figure 4), consistent with prior field trials in the US revealing heightened heat tolerance in warmer regions (Ristic *et al* 1996). This distinction stems from the fact that cultivars planted in the southern region: (a) exhibit a greater capacity to produce heat shock proteins and (b) possess morphologies better adapted to hot conditions relative to those planted in the northern region (Ristic *et al* 1996).

Moreover, we found the nonlinear relationship between precipitation and maize yields across three phenological period of maize. Previous studies (Doorenbos and Kassam 1979, Cakir 2004) have reported that maize appears to be relatively tolerant to water deficits during the vegetative and ripening periods. The greatest decrease in yields is caused by moisture deficit during the flowering period, which is consistent with our findings in this study (figure 3(c)). Besides the direct impact of precipitation, previous research also signifies its potential to alleviate the negative effects of high temperature by accounting for the interactive effects between cumulative seasonal (or monthly) rainfall and extreme heat (Schlenker and Roberts 2009, Leng 2019, Luan *et al* 2021). However, given the uneven nature of daily precipitation during heat periods (FTP) within a given year, long-term rain totals do not provide a comprehensive picture. Hence, this study pivots on understanding how the impacts of heat on maize yields can be modulated by FTP across three specific phenological periods. We found that FTP significantly weakens the sensitivity to EDD in each period (figure 3(a)). In general, influence of timely precipitation on temperature-yield relations could result from two primary mechanisms. First, it ensures the availability of water, maintaining soil moisture levels during periods of high temperatures (Dirmeyer *et al* 2009). Prior studies have indicated that soil moisture deficits substantially affect hot extremes through the energy balance: low soil moisture availability reduces evaporative cooling and increases atmospheric heating from sensible heat flux (Seneviratne *et al* 2010, Hirschi *et al* 2011). Second, existing heat stress can be attenuated by timely precipitation which not only satisfies the increased evapotranspiration demand due to higher temperatures but also cools the crop canopy (Siebert *et al* 2014). Precipitation can also lower the temperature of both the air and the soil. This cooling effect can help alleviate heat stress and prevent damage to crop. Furthermore, we analyzed the mitigating effect of FTP to EDD sensitivity at three specific phenological stages across both northern and southern regions (figure 4). Overall, the benefits from timely precipitation were more pronounced in the northern region compared to the southern region. This can result from frequent FTP in northern region relative to southern region (figure 2). Our study underscores and quantifies the mitigating influences of timely precipitation on the negative effects of heat on maize yields across various growth stages and regions, offering valuable insights into multifaceted climate-related challenges.

5. Conclusion

In summary, our study delves into the crucial role of timely precipitation in mitigating heat effects across the US Corn Belt, providing valuable insights into the broader understanding of the climate-crop relationship. We conducted analysis across various phenological periods and identified that increased FTP significantly weakens the sensitivity of maize yields to extreme heat. This finding underscores the necessity of incorporating timely precipitation as a pivotal factor when estimating heat effects in evolving climates, offering valuable insights for sustainable agricultural practices amidst ongoing climate change.

Acknowledgments

This study was supported by the U S National Science Foundation NSF Convergence Accelerator (#E2066263 and #FAIN:2345039) (XL) and USDA Agricultural Research Service (A22-0103-001) (XL). We thank Dr M.B. Kirkham for the discussion on the paper and for editing the manuscript. We also thank Steve Watson for editing and finalizing the paper. This manuscript is contribution number 125-011-J from the Kansas Agricultural Experiment Station.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://quickstats.nass.usda.gov/; https://www.ncei.noaa.gov/data/nclimgrid-daily/

Author contributions

Xiaomao Lin designed the study and wrote the manuscript. Haidong Zhao conducted data analysis and wrote the first draft of the manuscript. Lina Zhang and Nenghan Wan downloaded data and revised the manuscript. Tom J Avenson and Stephen M Welch interpreted the results and advised on presentation of the main findings.

Competing interests

The authors declare that they have no conflict of interest.

ORCID iDs

Xiaomao Lin https://orcid.org/0000-0002-0804-7853

References

Akaike H 2011 Akaike's information criterion *International Encyclopedia of Statistical Science* 25–25

Asseng S, Ewert F, Martre P, Rötter R P, Lobell D B, Cammarano D, Kimball B A, Ottman M J, Wall G W and White J W 2015 Rising temperatures reduce global wheat production *Nat. Clim. Change* **5** 143–7

Barlow K, Christy B, O'leary G, Riffkin P and Nuttall J 2015 Simulating the impact of extreme heat and frost events on wheat crop production: a review *Field Crops Research* **171** 109–19

Bolaños J and Edmeades G 1996 The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize *Field Crops Research* **48** 65–80

Borrás L and Vitantonio-Mazzini L N 2018 Maize reproductive development and kernel set under limited plant growth environments *J. Exp. Bot.* **69** 3235–43

Butler E E and Huybers P 2013 Adaptation of US maize to temperature variations *Nat. Clim. Change* **3** 68–72

Butler E E and Huybers P 2015 Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase *Environ. Res. Lett.* **10** 034009

Butler E E, Mueller N D and Huybers P 2018 Peculiarly pleasant weather for US maize *Proc. Natl Acad. Sci.* **115** 11935–40

Cakir R 2004 Effect of water stress at different development stages on vegetative and reproductive growth of corn *Field Crops Research* **89** 1–16

Cesaraccio C, Spano D, Duce P and Snyder R L 2001 An improved model for determining degree-day values from daily temperature data *Int. J. Biometeorol.* **45** 161–9

Cicchino M, Edreira J R and Otegui M E 2010 Heat stress during late vegetative growth of maize: effects on phenology and assessment of optimum temperature *Crop Sci.* **50** 1431–7

Crafts-Brandner S J and Salvucci M E 2002 Sensitivity of photosynthesis in a C4 plant, maize, to heat stress *Plant Physiol.* **129** 1773–80

Deryng D, Conway D, Ramankutty N, Price J and Warren R 2014 Global crop yield response to extreme heat stress under multiple climate change futures *Environ. Res. Lett.* **9** 034011

Dirmeyer P A, Schlosser C A and Brubaker K L 2009 Precipitation, recycling, and land memory: an integrated analysis *Journal of Hydrometeorology* **10** 278–88

Doorenbos J and Kassam A 1979 Yield response to water *Irrigation and Drainage Paper* **33** 257

Durre I, Arguez A, Schreck C J III, Squires M F and Vose R S 2022 Daily high-resolution temperature and precipitation fields for the contiguous united states from 1951 to present *J. Atmos. Oceanic Technol.* **39** 1837–55

Fritsch F N and Carlson R E 1980 Monotone piecewise cubic interpolation *SIAM J. Numer. Anal.* **17** 238–46

Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8

Hirschi M, Seneviratne S I, Alexandrov V, Boberg F, Boroneant C, Christensen O B, Formayer H, Orlowsky B and Stepanek P 2011 Observational evidence for soil-moisture impact on hot extremes in southeastern Europe *Nat. Geosci.* **4** 17–21

Koutsoyiannis D 2012 Clausius–Clapeyron equation and saturation vapour pressure: simple theory reconciled with practice *Eur. J. Phys.* **33** 295

Leng G 2019 Uncertainty in assessing temperature impact on US maize yield under global warming: the role of compounding precipitation effect *Journal of Geophysical Research: Atmospheres* **124** 6238–46

Lipiec J, Doussan C, Nosalewicz A and Kondracka K 2013 Effect of drought and heat stresses on plant growth and yield: a review *Int. Agrophys.* **27** 463–77

Lizaso J, Ruiz-Ramos M, Rodríguez L, Gabaldon-Leal C, Oliveira J, Lorite I, Sánchez D, García E and Rodríguez A 2018 Impact of high temperatures in maize: phenology and yield components *Field Crops Research* **216** 129–40

Lobell D B, Bänziger M, Magorokosho C and Vivek B 2011 Nonlinear heat effects on African maize as evidenced by historical yield trials *Nat. Clim. Change* **1** 42–5

Lobell D B, Bonfils C J, Kueppers L M and Snyder M A 2008 Irrigation cooling effect on temperature and heat index extremes *Geophys. Res. Lett.* **35** L09705

Lu E 2007 Understanding the effects of atmospheric circulation in the relationships between water vapor and temperature through theoretical analyses *Geophys. Res. Lett.* **34** L14811

Luan X, Bommarco R, Scaini A and Vico G 2021 Combined heat and drought suppress rainfed maize and soybean yields and modify irrigation benefits in the USA *Environ. Res. Lett.* **16** 064023

Mahto S S and Mishra V 2024 Global evidence of rapid flash drought recovery by extreme precipitation *Environmental Research Letters* **19** 044031

Menne M J, Durre I, Vose R S, Gleason B E and Houston T G 2012 An overview of the global historical climatology network-daily database *J. Atmos. Oceanic Technol.* **29** 897–910

Mueller B and Seneviratne S I 2012 Hot days induced by precipitation deficits at the global scale *Proc. Natl Acad. Sci.* **109** 12398–403

Ortiz-Bobea A and Just R E 2013 Modeling the structure of adaptation in climate change impact assessment *American Journal of Agricultural Economics* **95** 244–51

Ristic Z, Williams G, Yang G, Martin B and Fullerton S 1996 Dehydration, damage to cellular membranes, and heat-shock proteins in maize hybrids from different climates *J. Plant Physiol.* **149** 424–32

Sacks W J and Kucharik C J 2011 Crop management and phenology trends in the US Corn Belt: impacts on yields, evapotranspiration and energy balance *Agric. For. Meteorol.* **151** 882–94

Sadok W, Lopez J R and Smith K P 2021 Transpiration increases under high-temperature stress: potential mechanisms, trade-offs and prospects for crop resilience in a warming world *Plant, Cell & Environment* **44** 2102–16

Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to US crop yields under climate change *Proc. Natl Acad. Sci.* **106** 15594–8

Seneviratne S I, Corti T, Davin E L, Hirschi M, Jaeger E B, Lehner I, Orlowsky B and Teuling A J 2010 Investigating soil moisture–climate interactions in a changing climate: a review *Earth Sci. Rev.* **99** 125–61

Sharratt B, Zandlo J and Spoden G 2001 Frequency of precipitation across the northern US Corn Belt *Journal of Applied Meteorology and Climatology* **40** 183–91

Siebert S and Ewert F 2014 Future crop production threatened by extreme heat *Environ. Res. Lett.* **9** 041001

Siebert S, Ewert F, Rezaei E E, Kage H and Graß R 2014 Impact of heat stress on crop yield—on the importance of considering canopy temperature *Environ. Res. Lett.* **9** 044012

Tollenaar M, Fridgen J, Tyagi P, Stackhouse P W Jr and Kumudini S 2017 The contribution of solar brightening to the US maize yield trend *Nat. Clim. Change* **7** 275–8
Trenberth K E and Shea D J 2005 Relationships between precipitation and surface temperature *Geophys. Res. Lett.* **32** L14703
Van Aalst M K 2006 The impacts of climate change on the risk of natural disasters *Disasters* **30** 5–18
Wang Y, Sheng D, Zhang P, Dong X, Yan Y, Hou X, Wang P and Huang S 2021 High temperature sensitivity of kernel formation in different short periods around silking in maize *Environ. Exp. Bot.* **183** 104343
Wang Y, Tao H, Tian B, Sheng D, Xu C, Zhou H, Huang S and Wang P 2019 Flowering dynamics, pollen, and pistil contribution to grain yield in response to high temperature during maize flowering *Environ. Exp. Bot.* **158** 80–8
Zhao C, Liu B, Piao S, Wang X, Lobell D B, Huang Y, Huang M, Yao Y, Bassu S and Ciais P 2017 Temperature increase reduces global yields of major crops in four independent estimates *Proc. Natl Acad. Sci.* **114** 9326–31
Zhao H, Zhang L, Kirkham M, Welch S M, Nielsen-Gammon J W, Bai G, Luo J, Andresen D A, Rice C W and Wan N 2022 US winter wheat yield loss attributed to compound hot-dry-windy events *Nat. Commun.* **13** 7233
Zhu P, Kim T, Jin Z, Lin C, Wang X, Ciais P, Mueller N D, Aghakouchak A, Huang J and Mulla D 2022 The critical benefits of snowpack insulation and snowmelt for winter wheat productivity *Nat. Clim. Change* **12** 485–90