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RESEARCH ARTICLE

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Compounding precipitation effect in modulating maize yield response to global warming

Yunyun Ban | **Guoyong Leng** | **Qiuhong Tang**

Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, P. R. China

Correspondence
Guoyong Leng and Qiuhong Tang, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences, Chinese Academy of Sciences, Beijing 100101, P.R. China.
Email: tangqh@igsnrr.ac.cn; lenggy@igsnrr.ac.cn

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Abstract

High temperature generally causes large-scale crop yield reduction, and such negative effects are known to depend on the concurrent precipitation. However, the compounding precipitation effect in regulating crop yield response to global warming remains under-examined. This research aims to evaluate the role of concurrent changes in precipitation in modulating global maize yield response to temperature under 1.5 and 2.0 K temperature rise for RCP 4.5 and 8.5 scenarios, respectively. Empirical linear function is adopted to calculate the function parameters and impact of precipitation modulation based on global census data on maize yield and climate in the baseline period of 1980–2010. The sensitivity of maize yield to temperature is then estimated under condition that with and without removal of precipitation impact. The maize yield sensitivity to temperature is negative in most rain-fed growing areas in the baseline period of 1980–2010, and the global sensitivity is −9.39%/K if the precipitation impact is considered or −6.92%/K if the precipitation impact is removed. Globally, approximately 30% of the observed strength of relationship between maize yield and temperature is induced by the compounding precipitation effect. Under 1.5 and 2.0 K warming scenarios, global maize yield is projected to decrease by −10.16% to −11.91% and −15.01% to −17.14%, respectively. The world maize yield differences between 1.5 and 2.0 K scenarios will be −4.85% and −5.23% without the compounding precipitation effect and range from −3.52% to −3.89% with the compounding precipitation effect, to which the contribution of compounding precipitation increases to 35%. The modulating impacts of precipitation are the strongest in high latitude countries, while weak effects are found in Argentina, China, India, and South Africa. The research can help us understand the important but uncertain issue that how much the maize yield response to global warming is contributed by the compounding precipitation effect.

KEYWORDS

climate warming, maize yield, precipitation modulation, temperature impact

1 | INTRODUCTION

Growing global demand for food is expected to be doubled by the 2050s compared with that in 2014 (Hunter *et al*., 2017). Understanding the climate-food nexus and the climate effects on food production under the changing scenario is a prior to ensure food security and social sustainable development (Godfray *et al*., 2010; Tilman *et al*., 2011). Climate factors and their variations, such as temperature and precipitation, may have adverse influence on plant growth and development processes (Liu *et al*., 2016), which would likely deteriorate current hunger status in some areas (Wheeler and Joachim, 2013). In particular, the crop yield is more sensitive to climate extremes, which tends to be more frequent and severe based on future climate assessment. Research on climate effect on crop yield under climate change could assist decision-makers in agricultural policy formulation and adjustment, and guide farmers in crop growing and adaption (Lesk *et al*., 2016; Zampieri *et al*., 2017).

Crop yield is generally enslaved to photosynthesis, while crop growth is more vulnerable to temperature among different climate factors (Li *et al*., 2015; Lesk *et al*., 2016; Zipper *et al*., 2016). Suitable temperature is essential for crop growth and yield (Butler and Huybers, 2013; Deryng *et al*., 2016; Mall *et al*., 2016; Leng, 2017). Extreme temperature is closely related to crop yield change (Vogel *et al*., 2019), and high temperature has great adverse impact on crop (Flack-Prain *et al*., 2021). The high temperature greatly reduces crop yield by damaging crop internal structures and even kill the plants (Kadam *et al*., 2014; Qaiser *et al*., 2021). In addition, it weakens photosynthesis and material synthesis by increasing crop water requirement and soil moisture evaporation, which will gradually cause stomata closure, decrease absorption of CO_2, and thus reduce above-ground biomass accumulation (Siebert *et al*., 2017). The impact of temperature on crop yield becomes more complex when the relationship between yield and temperature (YT) is analyzed without removing concurrent precipitation because that precipitation and its variation affect the changes in crop growth and yield along with temperature. When drought occurs, crop stomata close to control water evaporation which results in inactive photosynthesis, leading to decreased crop yield (Leng and Hall, 2020). When flood comes, the water logging caused by excessive rain will also induce the decreased crop yield (Zampieri *et al*., 2017).

Temperature and precipitation together with other factors are introduced into statistical, process-based, and physiological models to assess the influence of the factors on crop yield (Li *et al*., 2015; Zhao *et al*., 2017). A large number of previous research has been conducted to characterize the impact of temperature on maize growth and development processes using crop models (Rosenzweig *et al*., 2014; Asseng *et al*., 2015). The temperature and precipitation impact on maize yield has been analyzed together in the former research (Rosenzweig *et al*., 2014; Wang *et al*., 2017). However, how the precipitation modulates the temperature influences on maize yield remains poorly understood. The compounding precipitation will amplify or underestimate the impact of temperature on yield, in addition, its substantial uncertainty under future global warming is the key aspect that requires deep understanding. Although some regional research has been done, works to explore the impacts of temperature on maize yield, especially for individual country, must exclude precipitation effects throughout the world (Lobell *et al*., 2011; Leng et al., 2019). Exploring the historical relationship and sensitivity among maize yield, temperature, and precipitation can assist us to gauge the significance of future climate change for food supply (Lobell *et al*., 2011).

In this research, the temperature impact on maize production will be investigated under condition that the effect of precipitation is removed beforehand by statistic method. Then, the maize yield change is predicted under 1.5 and 2.0 K global warming scenarios. To consider the modulating effects of precipitation on maize yield response to temperature, the crop yield affected by temperature with and without precipitation enhancement are calculated as a comparison. The objectives of this research are to (1) determine YT relations and maize yield sensitivity to temperature in historical period, (2) quantify how much the observed YT relation is actually contributed by precipitation modulating impact, and (3) identify the impact of precipitation on future projected maize yield under global warming scenarios. Although this paper researches maize yield, the study it will help understand the impact of precipitation on regulating YT relationship of other crop and contribute to specify the factors that take the leading position of future crop yield.

2 | MATERIALS AND METHODS

2.1 | Maize yield and climate data

Annual country level observed data on maize yield is obtained from the Food and Agriculture Organization (FAO, http://faostat.fao.org). Note that it cannot distinguish the rain-fed and irrigated maize yield completely. The period of 1980–2010 is selected as the reference period because such a period is the overlap between maize yield observations and simulations and both the climate and yield data are available. In this research, the top 10 countries, which accounts for 78% of global maize yield, are selected to build the empirical crop models which are applied to calculate precipitation impact in the 104 maize growing countries. To determine the global maize distribution, the MIRCA2000 data on global rain-fed crop area are acquired from the Institut für Physische Geographie, Goethe-Universität (http://www.uni-frankfurt.de/45218031) (Portmann *et al.*, 2010). Gridded monthly mean temperature and precipitation data at a spatial resolution of $0.5^\circ \times 0.5^\circ$ for the period of 1980–2010 is collected from the Climate Research Unit (CRU TS 4.01) (Mitchell and Jones, 2005).

While certain regions have two cropping seasons in a year, this study focuses on the major cropping season due to the limitation of data availability. Here, following Leng and Hall (2020), the major growing season is defined by the months of June, July, and August (JJA) for the northern hemisphere, and December, January, and February (DJF) for the southern hemisphere. Though potential uncertainty would be caused from the choice of growing season, Lobell *et al.* (2013) showed that the country-level relationship between maize yield and climate is quite insensitive to the choice of cropping season months.

2.2 | Model building and analytical method

Based on the maize area from MIRCA2000 and climate data from Climate Research Unit (CRU TS 4.01), we calculated the annual average temperature and precipitation over the rain-fed maize area in growing season in each of the top 10 countries. In this study, the annual time series of maize yield, precipitation, and temperature in growing season are linearly detrended, based on which the relationships between annual maize yield and climate variables are investigated. Subtracting the linear trend component from the annual time series can well eliminate the influence of technology progress and similar results are obtained when using incremental method for removing the effects of technology progress (Figure S1).

Besides temperature and precipitation, crop yield is determined by various factors such as radiation and CO_2. Agricultural management such as multiple cropping (Seifert and Lobell, 2015), irrigation (Leng, 2017), soil mulching (Qin *et al.*, 2015) and conservation tillage (Karlen *et al.*, 2013) could further complicate crop yield predictions. Instead of including as many as possible influencing factors for predicting the exact yield values, we investigate the yield sensitivity to temperature and precipitation variations, with a focus on the compounding effects of precipitation. Nevertheless, it is found that the linear function of temperature and precipitation against yields exhibits a good performance with $R = 0.77$ (Figure 2), which is consistent with previous empirical research (Ray *et al.*, 2015).

Specifically, the yield response to temperature change is first assessed based on the function below:

$$Y_{c,y} = a_1 T_{c,y} + \alpha_s + \varepsilon_{s,y} \tag{1}$$

where c represents the country; y is the year; $Y_{c,y}$ (t/ha), and $T_{c,y}$(K) the maize yield and temperature of a country in a certain year; a_1 is parameter, representing the sensitivity of maize yield to 1 K temperature change; α_s the intercept representing constant regional effects; $\varepsilon_{s,y}$ denotes error term. The yield changes affected by temperature as expressed in Equation 1 in each top 10 maize planting countries are fitted by least squares method to obtain the parameters. Though the non-linear relationship between maize yield and temperature is important in revealing their internal mechanism (Lobell *et al.*, 2013; Bassu *et al.*, 2014), this research mainly focuses on the modulation impact of precipitation on YT relationship. Therefore, the simple linear function is adopted in this research instead of non-linear equation.

The effect of temperature on maize yield at each country is then analysed by calculating average maize yield sensitivity to temperature. The sensitivity variation reflects the percentage change of maize yield to temperature fluctuations. In order to remove the regional differences among countries and make the data comparable, normalization is introduced by calculating the ratio between a_1 and average maize yield, as defined:

$$S_{(Y,T)} = \frac{a_1}{\overline{Y}_{c,y}} \times 100\% \tag{2}$$

where $S_{(Y,T)}$ is normalized sensitivity of maize yield to temperature, %/K, which can reflect the influence of different temperature on maize yield. $\overline{Y}_{c,y}$ is the average maize yield in the baseline period of 1980–2010.

The temperature effect on maize yield calculated by Equation 1 includes the concurrent impact of precipitation. It is necessary to remove the modulating impact of precipitation to analyse the temperature effect alone on maize yield instead of their compound effect. In this research, the influence factor such as precipitation is removed before exploring the relationship between crop yield and temperature. The following functions are used to exclude the compounding influences of precipitation. The maize yield and temperature are all regressed by precipitation as:

$$Y^*_{c,y} = b_1 P_{c,y} + b_0 \tag{3}$$

$$T^*_{c,y}=c_1P_{c,y}+c_0 \quad (4)$$

$Y^*_{c,y}$ and $T^*_{c,y}$ are the maize yield and growing-season temperature represented by precipitation ($P_{c,y}$) of a country in a certain year. b_0, b_1, c_0, and c_1 are parameters. To investigate the sensitivity of maize yield to temperature increase with removal of precipitation impact $S_{(Y,T)|P}$, the residuals $Y'_{c,y}$ and $T'_{c,y}$ that represent maize yield and temperature after removing precipitation impact are calculated by following equations:

$$Y'_{c,y}=Y^*_{c,y}-Y_{\text{obs}} \quad (5)$$

$$T'_{c,y}=T^*_{c,y}-T_{\text{obs}} \quad (6)$$

where Y_{obs} and T_{obs} are observed yield and temperature, respectively. Equations 5 and 6 are substituted into Equation 1.

$$Y'_{c,y}=\alpha'_1T'_{c,y}+\alpha'_s+\varepsilon'_{s,y} \quad (7)$$

α'_1 is parameter, representing maize yield sensitivity to temperature after removing precipitation impact; α'_s is the intercept, representing constant regional effects with removal of precipitation impact, $\varepsilon'_{s,y}$ denotes error term. The maize yield sensitivity to temperature without the compounding precipitation effect can be estimated by Equation 8.

$$S_{(Y,T)P}=\frac{\alpha'_1}{\overline{Y'_{c,y}}}\times 100\% \quad (8)$$

where $S_{(Y,T)|\text{P}}$ is normalized sensitivity of maize yield to temperature after removing precipitation impact, %/K. $\overline{Y'}_{c,y}$ is the average maize yield with removal of precipitation impact during the period of 1980–2010. The precipitation impact in modulating YT relations is calculated by comparing the difference between $S_{(Y,T)}$ and $S_{(Y,T)|\text{P}}$

$$M_P=S_{(Y,T)}-S_{(Y,T)|\text{P}} \quad (9)$$

where M_P is modulating impact of precipitation on YT relations (%/K) and showed in Figure 1.

2.3 | Global maize yield estimation under 1.5 and 2.0 K warming

Maize yield changes at global mean temperature increases of 1.5 and 2.0 K are analysed here. Firstly, the year of global average temperature rising by 1.5 or 2.0 K compared with the level of last industrialization (1860–1890) (Greve *et al.*, 2018; Samaniego *et al.*, 2018) is calculated by analysis of the four global climate models (GCMs) temperature data. The historical simulation period between 1860 and 1890 is selected to represent the climate state before the industrial revolution. We estimate future global maize yield for different Representative Concentration Pathways (RCP4.5 and RCP8.5). The variation in maize yield in growing countries affected by historical and future temperature is adopted to explore the possible increase or decrease under the global warming conditions of 1.5 and 2.0 K, respectively. To eliminate the uncertainty caused by interannual change, we select the projected year and 5 years before and after the projected year (11 years in total) as period of 1.5 and 2.0 K temperature rise in different emission scenarios. The years predicted by different GCMs for the global average surface temperature to reach the expected temperature represent the center years of the moving average (Joshi *et al.*, 2015). The results are shown in Table 1 for RCP4.5 and RCP8.5 for each of five GCM models.

The change of global maize yield by increase in temperature of 1.5 K is expressed as $\Delta^{1.5k}_{(Y,T)}$, and the change by removing the impact of precipitation is $\Delta^{1.5k}_{(Y,T)|P}$. Similarly, maize yield change caused by the 2.0 K climate warming is expressed as $\Delta^{2.0k}_{(Y,T)}$ and as $\Delta^{2.0k}_{(Y,T)|P}$ with removal of precipitation. A common hypothesis in previous research is that the statistic-based crop models established by history data will still be valid in the future (Xiao *et al.*, 2020). The future yield changes are estimated by the historical sensitivity to temperature based on Equations 2 and 8 to illustrate how the combined precipitation modulates yield response to temperature rise under global warming:

$$\Delta^{1.5K}_{(Y,T)}=S_{(Y,T)}\times\left(T^{1.5K}_{c,y}-T_{c,y}\right) \quad (10)$$

$$\Delta^{1.5K}_{(Y,T)|P}=S_{(Y,T)|P}\times\left(T^{1.5K}_{c,y}-T_{c,y}\right) \quad (11)$$

$$\Delta^{2.0K}_{(Y,T)}=S_{(Y,T)}\times\left(T^{2.0K}_{c,y}-T_{c,y}\right) \quad (12)$$

$$\Delta^{2.0K}_{(Y,T)|P}=S_{(Y,T)|P}\times\left(T^{2.0K}_{c,y}-T_{c,y}\right) \quad (13)$$

where $T^{1.5K}_{c,y}$ and $T^{2.0K}_{c,y}$ are future temperature under 1.5 and 2.0 K global warming of a country in a certain year. The potential benefit is analyed by the difference in projected maize yield between the 1.5 and 2.0 K temperature rise to address the modulating impact of precipitation on maize yield response to climate warming.

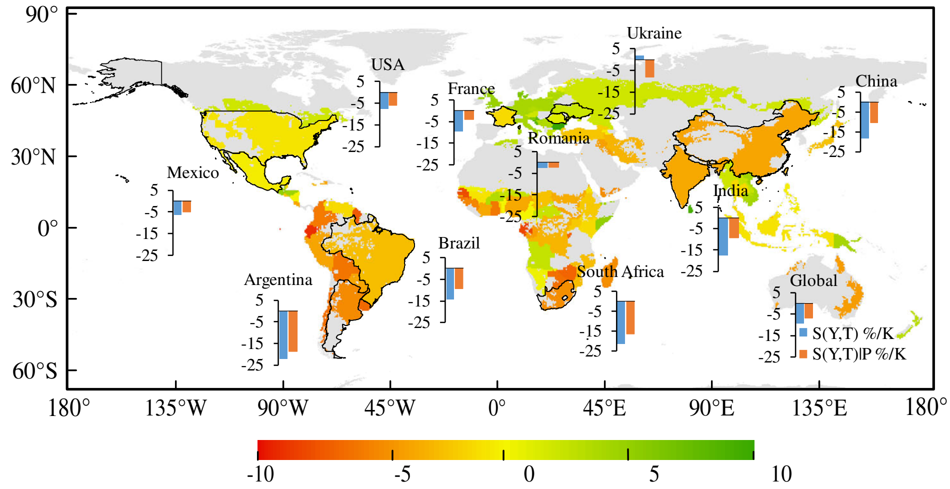

FIGURE 1 The distributions of precipitation modulating impact on YT relations. Yield change to temperature growth (1 K) under conditions that with (S[Y,T]) and without (S[Y,T]|P) compounding precipitation impact estimated using FAO maize yield and CRU TS 4.01 climate data during 1980–2010 period. The S(Y,T) and S(Y,T)|P in top 10 countries are selected for illustration (colour bars). The map shows the in each maize rain-fed country. There are total 104 countries in the map [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 1.5 and 2.0 K warming year predicted by four global climate models compared to the last industrialization (1860–1890) levels

		1.5 K		2.0 K	
	Models	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
GCMs	GFDL-ESM2M	2011	2023	2037	2033
	HadGEM2-ES	2028	2030	2041	2032
	IPSL-CM5A-LR	2017	2011	2028	2023
	MIROC-ESM-CHEM	2029	2024	2041	2038

3 | RESULTS AND DISCUSSIONS

3.1 | Effects of precipitation on YTrelationship in historical period

The correlation changes year by year of maize yield from 1980 to 2010 are showed in Figure 2. There is a significant negative relationship between maize yield and temperature over most of the maize growing countries in the Southern Hemisphere. In the Northern Hemisphere, however, the negative correlation between temperature and maize yield becomes much weaker. Moreover, there is a positive correlation between these two over the high latitude countries, where temperature appears the primary factor that controls the crop growth. Such a finding is, in general, consistent with the previous results reported by Butler and Huybers (2013) and Leng (2019). The positive relationship between maize yield and temperature (*R*[Y,T] in Figure 2a) in Northern Hemisphere indicate the growing-season temperature cannot reach the suitable degree for maize growth, therefore, temperature rise will bring increase in maize yield. Precipitation also has significant impact on maize yield across maize growing countries (Figure 2b). Much of *R*(Y,P) shows that greater precipitation prompt higher maize yield, except for certain countries near the Equator such as Brazil. The indirect impact of precipitation on maize yield could be reflected by its interaction with temperature. Generally, although temperature has close relationship with radiation or cloud, it is higher in drier days all over the world (Tang and Leng, 2013; Chiang *et al.*, 2018). The *R*(T,P) in Figure 2c shows numerous Northern Hemisphere countries have weak correlation between temperature and precipitation, but the strong negative correlation appears in most countries that are located in the Southern Hemisphere. The significant relations in Figure 2 lead to the issue that how much the YT relation is modulated by precipitation.

Simulations are performed for 104 countries in different years to evaluate the reliability of maize yield by Equation 1 (Figure 3). Linear regression which empirically fit the yield-temperature relation indicates that approximately 77% of global maize yield variability is induced by temperature change. In Figure 3, the

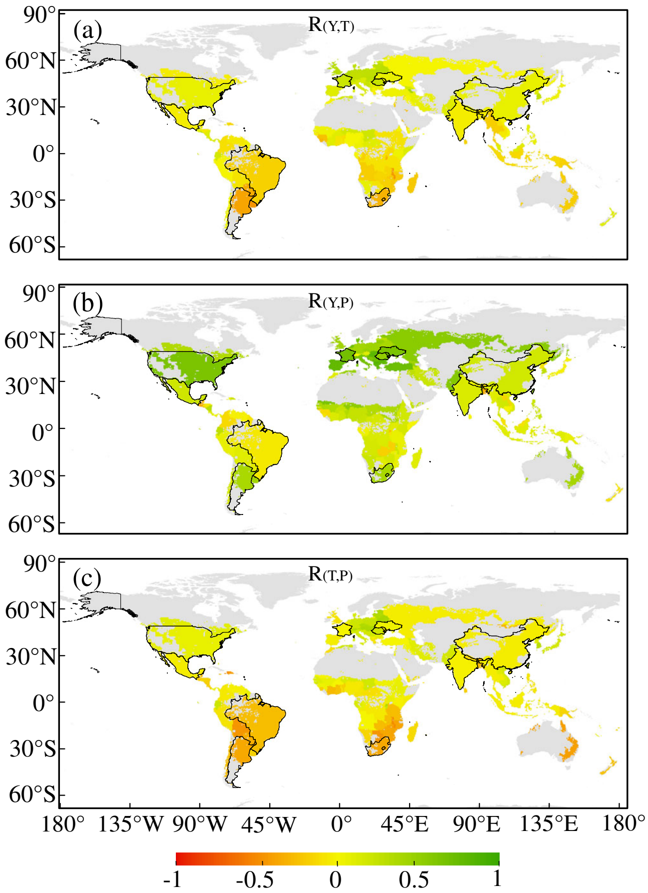

FIGURE 2 Correlation between maize yield and temperature (R[Y,T]) (a), maize yield and precipitation (R[Y,P]) (b), and temperature and precipitation (R[T,P]) (c) over 104 rainfed maize growing countries from 1980 to 2010. The top 10 countries are outlined for illustration [Colour figure can be viewed at wileyonlinelibrary.com]

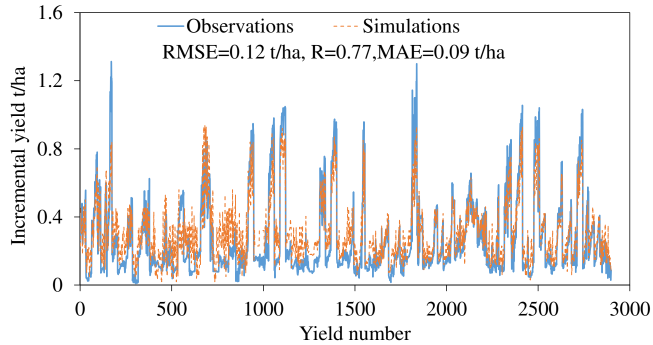

FIGURE 3 Comparison between observed (blue line) and simulated (orange line) maize yield of 104 countries in different years (horizontal ordinate). The simulations are calculated by Equation (1). The Root Mean Squared Error (RMSE) and correlation coefficient (R) between observations and simulations are shown [Colour figure can be viewed at wileyonlinelibrary.com]

simulations by Equation 1 has the similar tendency to the observations. However, the extreme is relatively poor fitted and fluctuation range of simulations is smaller than the observations, reflecting the Equation 1 fits the medium well instead of the extremes. In addition, the RMSE and MAE (1.15 t/ha and 0.98) show that the dispersion and error are within a reasonable range, indicating the model accuracy is enough to simulate YT relations of maize.

The precipitation modulating impact is estimated using observations during 1980–2010 and YT relationships with and without consideration of the compounding influences of precipitation (i.e., $S_{(Y,T)}$ and $S_{(Y,T)|P}$) of maize yield at 104 countries are showed in Figure 1. The lowest three values among the top 10 countries that maize yield sensitivity to temperature $S_{(Y,T)}$ appear in Argentina, South Africa, and China, respectively, while the highest three countries are Ukraine, Romania, and Mexico. One notable exception is the positive $S_{(Y,T)}$ in Ukraine, where temperature rise leads to higher maize yield. Although the sensitivity ($S_{(Y,T)|P}$) of maize yield to temperature calculated by Equation (8) shows the same lowest countries as $S_{(Y,T)}$, the highest three countries are Romania, France, and Mexico. The precipitation impact in modulating the YT relations (M_P) showed in Figure 1 indicates that the countries with the most obvious regulation impact of precipitation among the top 10 countries are Ukraine, India, and China.

$S_{(Y,T)}$ and $S_{(Y,T)|P}$ in 104 countries during the 1980–2010 baseline period range from −42 to 49%/K and show the positive linear correlation, suggesting that influences of temperature on maize yield are mostly similar before or after the removal of precipitation impact. The mean M_P is −2.47%/K, which represent that the precipitation impact has the strength of approximately 30% on the YT relationship. In certain countries such as Ukraine and South Africa, the impact of precipitation on the YT relation could even reach more than 40%.

The positive sensitivity value in Figure 1 shows the positive precipitation modulating effect in affecting YT relation (Leng, 2019), and the temperature in those areas (the high latitude areas which are green or yellow-green in Figure 1) is lower than other countries as shown in Table 2. Therefore, the maize yield will benefit from temperature rise in these areas. However, the precipitation modulating impact in the form of drought and flood driven by deficiency or excessiveness of precipitation will seriously threaten crop yield (Ibrahim *et al.*, 2021). Drought frequently occurs in sub-humid and semi-arid regions and aggravates the linearly negative YT relationship (Adejuwon and Olaniyan, 2018). However, increase in precipitation at the initial stage makes maize yield continue rising until it becomes waterlog (Leng, 2019).

TABLE 2 Global precipitation modulating impact on YT relation of top 10 countries

	Temperature	$\Delta_{M_P}^{1.5k}$ (%/K)		$\Delta_{M_P}^{2.0k}$ (%/K)	
Maize growing country	K	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Argentina	297.12	−4.20	−4.53	−5.67	−6.95
Brazil	295.84	−3.16	−3.78	−4.38	−5.26
China	296.80	−4.87	−4.92	−5.35	−5.53
France	294.38	−1.94	−3.67	−3.97	−5.25
India	300.72	−3.55	−4.19	−4.36	−4.93
Mexico	296.55	−1.49	−1.54	−2.15	−2.97
Romania	292.90	−0.42	−0.17	−1.25	−2.23
South Africa	297.46	−4.25	−5.50	−5.45	−6.47
Ukraine	293.45	3.90	−0.92	−1.02	−1.64
USA	296.08	−2.01	−2.59	−2.44	−2.93
Global average	296.14	−2.20	−3.18	−3.60	−4.42

The vertical ordinate of Figure 4a shows the correlation between temperature and precipitation, and the horizontal ordinate is the impact of precipitation in modulating YT relations. The correlation between precipitation and temperature is negative in most maize growing regions (Figure 4a). The maize yield sensitivity to temperature ranges between −20 and 0%/K across countries (Figure 4a). The precipitation modulating effect around 0%/K may be caused by the mismatch between the maize growing season and the period when intensive precipitation occures. In addtion, higher evaporation induced by rise temperature in the the hot and humid maize growing regions may also plays a key role in this phenomenon, such as regions in Africa with low M_P in Figure 3 (Welch *et al.*, 2010; Rowhani *et al.*, 2011). Higher correlation between temperature and precipitation with high precipitation modulating impact indicates the important impact of precipitation on maize yield in arid and semi-arid regions (Chen *et al.*, 2018; Leng, 2019).

The vertical ordinate of Figure 4b shows the correlation between maize yield and precipitation, and the horizontal ordinate is the precipitation modulating impact on YT relation. It shows obvious opposite trend between $R_{(Y,P)}$ and precipitation regulation impact (M_P) with high determination coefficient of −0.67. The high correlation coefficient corresponds to the wide distribution of precipitation regulation approximately ranged from −45 to −5%/K. Precipitation not only significantly promotes high maize yield, but also greatly modulates YT relations in arid and semi-arid areas (Schierhorn *et al.*, 2020). Therefore, precipitation potentially has positive impact on crop growth and yield in rain-fed areas (Konapala *et al.*, 2020), and results in higher crop yield owing to the combination of suitable temperature and drought (Schierhorn *et al.*, 2020).

The correlation coefficient of relationship between yield and precipitation ($R_{(Y,P)} = -0.67$) is much higher than that between temperature and precipitation ($R_{(T,P)} = 0.27$). This indicates that the compounding influences of precipitation on YT relationship is directly caused by the precipitation contribution to yield instead of indirectly resulting from precipitation and temperature relations (Figure 4a,b). These results contribute to deep understanding of what the main way precipitation affects YT relationship.

3.2 | The future maize yield change under 1.5 and 2.0 K global warming

The percentage change of maize yield to temperature with and without concurrent precipitation impact is calculated by four GCM models as shown in Table 1. This study does not take the impact of extreme event into account, but only considers the impact of changes in annual mean temperature and precipitation. The forecast of future maize yield change is conducted based on the hypothesis that the future YT relationship, precipitation, and the maize growing area remain unchanged (Urban *et al.*, 2015; Leng, 2019), and no additional management and other factors are considered in this research.

The maize yield will be potentially affected by higher temperature and the extent is analysed by preserving precipitation influence. The expected change in maize yield is under conditions that global temperature increase 1.5 and 2.0 K rather than future yield changes in specific periods. The rising temperature impact on maize yield is firstly analysed without removing precipitation effects. Results show that the average crop yield of 104 maize growing countries will decrease approximately by

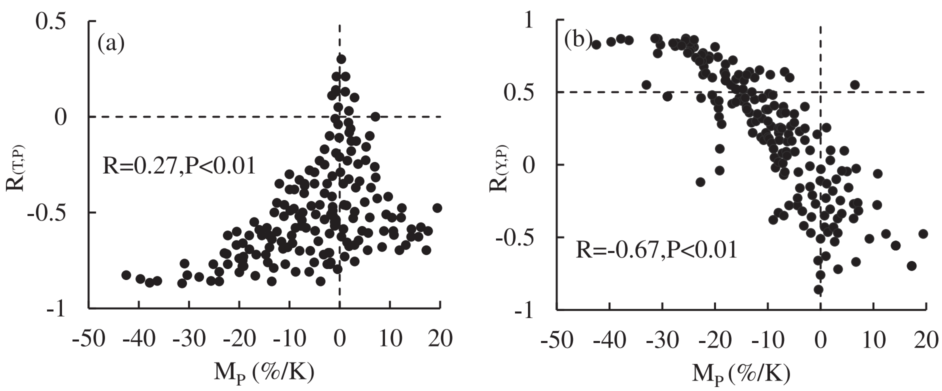

FIGURE 4 The relation of MP and relationships between precipitation and temperature (a) and between precipitation and yield (b). The same maize yield sensitivity data is adopted as those in Figure 2. Every point represents the maize yield in each country. There are total 104 points in each panel

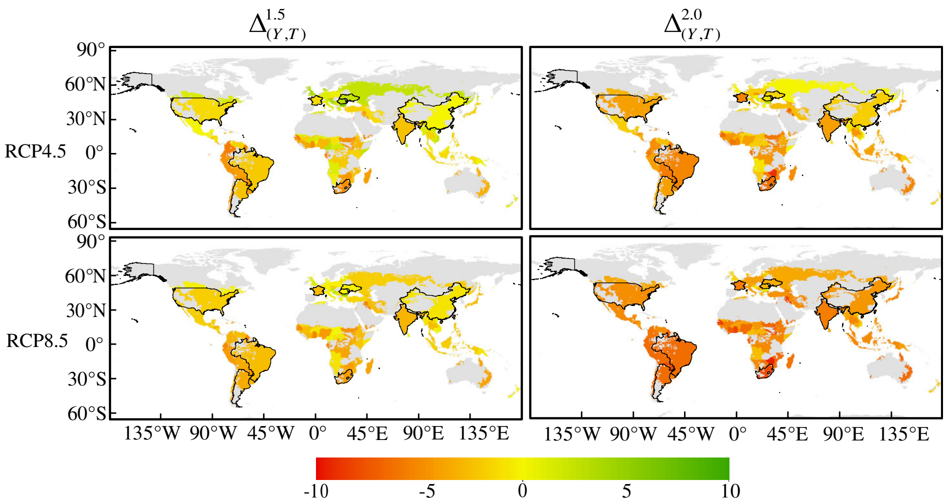

FIGURE 5 Expected percentage change in 104 maize growing countries related to temperature increase by 1.5 and 2.0 K under Representative Concentration Pathways (RCP) 4.5 and RCP8.5. The empirical model enables the average maize yield changes to predict under different climate scenarios and the results are shown. The top 10 maize growing countries are outlined for illustration [Colour figure can be viewed at wileyonlinelibrary.com]

−15.01% to −17.14% for different scenarios of RCP4.5 and RCP8.5 under condition that global mean temperature rise by 2.0 K (Figure 5, calculated by Equation 13). The result is similar to the research that each Degree-Celsius increase in global mean temperature will reduce maize yield by 7.4% (Zhao *et al.*, 2017). Another research shows 1.0 K increase in temperature results in a maize yield decline of approximately 10% relative to the 1951–1980 baseline in Iowa of United States (Ummenhofer *et al.*, 2015). It is projected that global temperature increases by 2.0 K decrease average maize yield by 13% in East Africa (Rowhani *et al.*, 2011). Rain-fed maize yield in southeast Africa may loss up to 14% compared with baseline period of 1971–2000 by 1.31 to 2.15 K warming due to climate change. The maize yield is more sensitive to temperature in the planting areas (Liu *et al.*, 2020) leading to that negative impact of increased temperature on future maize yield, which is projected in main maize growing countries such as United States, France, China, Brazil, Argentina, Ukraine, and India (Butler and Huybers, 2013; Zhao *et al.*, 2017; Tigchelaar *et al.*, 2018; Leng, 2019). Analysis of maize data shows that temperature up to 30 K results in severe and nonlinear decrease in yields in the Midwest United States (Lobell *et al.*, 2013), and a positive but weak response to seasonal precipitation (Ummenhofer *et al.*, 2015). All above previous research indicates the feasibility of our research method and the correctness of the results. The dominant factors of precipitation and temperature that affect maize yield are the basic reasons that obtain similar research results (Xiao *et al.*, 2020). The expected maize yield is estimated without influence of adaptation, management, and CO_2 fertilization so as to represent the upper limit of temperature rise impact on yield change. However, it is not the exact estimation result under uncertainty of groundwater and irrigation in the future.

The average change in maize yield is estimated by Equation 11 to decrease by −10.16% to −11.91% for different scenarios of RCP4.5 and RCP8.5 under 1.5 K global temperature rise. It indicates that limiting global warming to 1.5 K would reduce maize yield loss by 4.85% to 5.23% (Figure 5) compared with 2.0 K global warming. The most benefited regions are high latitude countries, such as Romania, Ukraine, and France. This projected distribution in high latitude regions is mainly due to the low growing season temperature once, which is meaningful for crop management. Moreover, research shows maize yield will benefit from warming scenarios by the more suitable temperature in the relatively colder areas (Chen *et al.*, 2018).

However, the projected maize yield under 1.5 K global warming will be affected by precipitation, resulting in lower crop production increase. The world maize yield difference between 1.5 and 2.0 K will range from 3.52% to 3.89% if the precipitation effect is removed (Figure 5), demonstrating approximately 35% of change in global maize yield is affected by precipitation. This result indicates that the modulating contribution of future precipitation will rise from 30% in the baseline period to 35% in the future. The maize yield decrease may be as a result of increasing drought stress in the warming scenario of 1.5 K (Chen *et al.*, 2018). In addition, global precipitation modulating impact on YT relation (M_P) is calculated under conditions that global temperature increase 1.5 and 2.0 K for different scenarios of RCP4.5 and RCP8.5, and the M_P of top ten countries and global average are listed in Table 2. The global average M_P under condition of global warming are all negative and lower than that in the baseline period (−2.47%/K), indicaing the higher strength of precipitation modulaing impact. Generally, the top four countries in Table 2 with the lowest M_P are Argentina, China, India, and South Africa.

Opportunities for increase in maize yield under global warming scenario are available if the suitable management such as fertilizer use and irrigation can be taken to regulate maize yield (Mueller *et al.*, 2012), especially water conservancy facilities in the areas near the equator. This study addresses the issue that how precipitation modulates the global maize YT relationship which is significant but uncertain in the past research. The negative impacts of higher temperature on future maize yield are generally caused by the decrease in growth duration and the exacerbation of the influences of extreme events (Chen *et al.*, 2018).

4 | CONCLUSION

Temperature effects have attracted more and more attentions in climate impact on crop yield estimation and dominate future change tendency in yield. This research analyses the compounding impacts of precipitation in modulating YT relationship for the historical period of 1980–2010 and for the future period with 1.5 and 2.0 K warming scenarios. It is found that precipitation mainly exerts its impacts directly through affecting maize yield, while the indirect impact through the feedback to temperature appears much little. The sensitivity of global maize yield to growing-season temperature in the baseline period is −9.39%/K, which could be reduced to −6.92%/K when the compounding precipitation effects were excluded, indicating precipitation modulating impact on spatial distribution of global maize yield driven by temperature is −2.47%/K. About 30% of the YT relationship results from the combined precipitation impacts, which is mainly resulted from the direct impact of precipitation on maize yield.

With regard to the future period with different temperature increasing scenarios, this study found that the 1.5 and 2.0 K will increase in temperature decrease the global maize yield from −10.16% to −11.91% and from −15.01% to −17.14% for different scenarios of RCP4.5 and RCP8.5, respectively. The contribution of precipitation modulating impact to future YT relation will rise to around 35% temperature and the strength will also be greater.

This research highlights the important role that precipitation plays in regulating YT relations. It also contributes to our understanding of future temperature rise impact on maize yield under the compounding impacts of precipitation which is an essential step for crop adaptation and management. This research clarifies the key role of precipitation in modulating maize yield to temperature and improves our understanding on fundamental YT relations.

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AUTHOR CONTRIBUTIONS

Yunyun Ban: Data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Guoyong Leng**: Data curation; formal analysis; supervision; investigation; methodology; resources; software; validation; visualization; writing – original draft; writing – review editing. **Qiuhong Tang:** Formal analysis; funding acquisition; project administration; supervision; visualization; writing – review and editing.

ORCID

Qiuhong Tang https://orcid.org/0000-0002-0886-6699

REFERENCES

Adejuwon, J. and Olaniyan, S. (2018) Drought occurrence in the sub-humid eco-climatic zone of Nigeria. *Theoretical and Applied Climatology*, 137, 1625–1636.

Asseng, S., Ewert, F., Martre, P., Rötter, R.P., Lobell, D.B., Cammarano, D., Kimball, B.A., Ottman, M.J., Wall, G.W., White, J.W., Reynolds, M.P., Alderman, p.D., Prasad, p.V.V., Aggarwal, p.K., Anothai, J., Basso, B., Biernath, C., Challinor, A.J., de Sanctis, G., Doltra, J., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Koehler, A.K., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ruane, A.C., Semenov, M.A., Shcherbak, I., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, p.J., Waha, K., Wang, E., Wallach, D., Wolf, J., Zhao, Z. and Zhu, Y. (2015) Rising temperatures reduce global wheat production. *Nature Climate Change*, 5(2), 143–147.

Bassu, S., Brisson, N., Durand, J.L., Boote, K., Lizaso, J., Jones, J. W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijn, S., Corbeels, M., Deryng, D., de Sanctis, G., Gayler, S., Grassini, P., Hatfield, J., Hoek, S., Izaurralde, C., Jongschaap, R., Kemanian, A.R., Kersebaum, K.C., Kim, S.H., Kumar, N.S., Makowski, D., Müller, C., Nendel, C., Priesack, E., Pravia, M.V., Sau, F., Shcherbak, I., Tao, F., Teixeira, E., Timlin, D. and Waha, K. (2014) How do various maize crop models vary in their responses to climate change factors? *Global Change Biology*, 20(7), 2301–2320.

Butler, E. and Huybers, P. (2013) Adaptation of US maize to temperature variations. *Nature Climate Change*, 3(1), 68–72.

Chen, Y., Zhang, Z. and Tao, F. (2018) Impacts of climate change and climate extremes on major crops productivity in China at a global warming of 1.5 and 2.0 °C. *Earth System Dynamics*, 9, 543–562.

Chiang, F., Mazdiyasni, O. and AghaKouchak, A. (2018) Amplified warming of droughts in southern United States in observations and model simulations. *Science Advances*, 4(8), eaat2380.

Deryng, D., Elliott, J., Folberth, C., Müller, C., Pugh, T.A.M., Boote, K.J., Conway, D., Ruane, A.C., Gerten, D., Jones, J.W., Khabarov, N., Olin, S., Schaphoff, S., Schmid, E., Yang, H. and Rosenzweig, C. (2016) Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity. *Nature Climate Change*, 6(8), 786–790.

Flack-Prain, S., Shi, L., Zhu, P., Rocha, H.R., Cabral, O., Hu, S. and Williams, M. (2021) The impact of climate change and climate extremes on sugarcane production. *GCB Bioenergy*, 13(3), 408–424.

Godfray, H., et al. (2010) Food security: the challenge of feeding 9 billion people. *Science*, 327(5967), 812–818.

Greve, P., Gudmundsson, L. and Seneviratne, S. (2018) Regional scaling of annual mean precipitation and water availability with global temperature change. *Earth System Dynamics*, 9, 227–240.

Hunter, M., Smith, R., Schipanski, M., Atwood, L. and Mortensen, D. (2017) Agriculture in 2050: Recalibrating targets for sustainable intensification. *Bioscience*, 67, 385–390.

Ibrahim, N., Vondou, A., Dassou, E., Ayugi, B. and Nouayou, R. (2021) Assessment of agricultural drought during crop-growing season in the sudano-sahelian region of Cameroon. *Natural Hazards*, 106, 561–577.

Kadam, N., et al. (2014) Agronomic and physiological responses to high temperature, drought, and elevated CO_2 interactions in cereals. *Advances in Agronomy*, 127, 111–156.

Karlen, D., Kovar, J., Cambardella, C. and Colvin, T. (2013) Thirty-year tillage effects on crop yield and soil fertility indicators. *Soil and Tillage Research*, 130, 24–41.

Konapala, G., Mishra, A., Wada, Y. and Mann, M. (2020) Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications*, 11(1), 1–10.

Leng, G. (2017) Evidence for a weakening strength of temperature-corn yield relation in the United States during 1980–2010. *Science of the Total Environment*, 605, 551–558.

Leng, G. (2019) Uncertainty in assessing temperature impact on u.s. maize yield under global warming: the role of compounding precipitation effect. *Journal of Geophysical Research-Atmospheres*, 124, 6238–6246.

Leng, G. and Hall, J. (2020) Predicting spatial and temporal variability in crop yields: an inter-comparison of machine learning, regression and process-based models. *Environmental Research Letters*, 15, 0044027.

Lesk, C., Rowhani, P. and Ramankutty, N. (2016) Influence of extreme weather disasters on global crop production. *Nature*, 529(7584), 84–87.

Li, T., Hasegawa, T., Yin, X., Zhu, Y., Boote, K., Adam, M., Bregaglio, S., Buis, S., Confalonieri, R., Fumoto, T., Gaydon, D., Marcaida, M., III, Nakagawa, H., Oriol, P., Ruane, A.C., Ruget, F., Singh, B., Singh, U., Tang, L., Tao, F., Wilkens, P., Yoshida, H., Zhang, Z. and Bouman, B. (2015) Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. *Global Change Biology*, 21, 1328–1341.

Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D.B., Martre, P., Ruane, A.C., Wallach, D., Jones, J.W., Rosenzweig, C., Aggarwal, p.K., Alderman, p.D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng, D., Sanctis, G.D., Doltra, J., Fereres, E., Folberth, C., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Kimball, B.A., Koehler, A.K., Kumar, S.N., Nendel, C., O'Leary, G.J., Olesen, J.E., Ottman, M.J., Palosuo, T., Prasad, p.V.V., Priesack, E., Pugh, T.A.M., Reynolds, M., Rezaei, E.E., Rötter, R.P., Schmid, E., Semenov, M.A., Shcherbak, I., Stehfest, E., Stöckle, C.O., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wall, G. W., Wang, E., White, J.W., Wolf, J., Zhao, Z. and Zhu, Y. (2016) Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, 6(12), 1130–1136.

Liu, D., Mishra, A. and Ray, D. (2020) Sensitivity of global major crop yields to climate variables: a non-parametric elasticity analysis. *Science of the Total Environment*, 748, 141431.

Lobell, D., Schlenker, W. and Costa-Roberts, J. (2011) Climate trends and global crop production Since 1980. *Science*, 333, 616–620.

Lobell, D., Hammer, G., McLean, G., Messina, C., Roberts, M. and Schlenker, W. (2013) The critical role of extreme heat for maize production in the United States. *Nature Climate Change*, 3, 497–501.

Mall, R., Sonkar, G., Bhatt, D., Sharma, N., Baxla, A. and Singh, K. (2016) Managing impact of extreme weather events in sugarcane in different agro-climatic zones of Uttar Pradesh. *Mausam*, 67(1), 233–250.

Mitchell, T. and Jones, P. (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, 25(6), 693–712.

Mueller, N., Gerber, J., Johnston, M., Ray, D., Ramankutty, N. and Foley, J. (2012) Closing yield gaps through nutrient and water management. *Nature*, 490, 254–257.

Qaiser, G., Tariq, S., Shahzada, A. and Latif, M. (2021) Evaluation of a composite drought index to identify seasonal drought and its associated atmospheric dynamics in Northern Punjab, Pakistan. *Journal of Arid Environments*, 185, 104332.

Qin, W., Hu, C. and Oenema, O. (2015) Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. *Scientific Reports*, 5, 16210.

Portmann, F., Siebert, S. and Döll, P. (2010) MIRCA2000 – Global monthly irrigated and rain-fed crop areas around the year 2000: A new high-resolution data set for agricultural and hydro- logical modeling. *Global Biogeochemical Cycles*, 24, 1–24.

Ray, D., Gerber, J., MacDonald, G. and West, P. (2015) Climate variation explains a third of global crop yield variability. *Nature Communications*, 6(1), 5989.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H. and Jones, J.W. (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the USA*, 111, 3268–3273.

Rowhani, P., Lobell, D., Linderman, M. and Ramankutty, N. (2011) Climate variability and crop production in Tanzania. *Agricultural and Forest Meteorology*, 151(4), 449–460.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E.F. and Marx, A. (2018) Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, 8(5), 421–426.

Seifert, C. and Lobell, D. (2015) Response of double cropping suitability to climate change in the United States. *Environmental Research Letters*, 10(2), 024002.

Schierhorn, F., Hofmann, M., Adrian, I., Bobojonov, I. and Müller, D. (2020) Spatially varying impacts of climate change on wheat and barley yields in Kazakhstan. *Journal of Arid Environments*, 178, 104164.

Siebert, S., Webber, H., Zhao, G. and Ewert, F. (2017) Heat stress is overestimated in climate impact studies for irrigated agriculture. *Environmental Research Letters*, 12(5), 054023.

Tang, Q. and Leng, G. (2013) Changes in cloud cover, precipitation, and summer temperature in North America from 1982 to 2009. *Journal of Climate*, 26(5), 1733–1744.

Tilman, D., Balzer, C., Hill, J. and Befort, B. (2011) Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the USA*, 108(50), 20260–20264.

Tigchelaar, M., Battistia, D., Naylorb, R. and Ray, D. (2018) Future warming increases probability of globally synchronized maize production shocks. *Proceedings of the National Academy of Sciences of the USA*, 115(26), 6644–6649.

Ummenhofer, C., Xu, H., Twine, T., Girvetz, E., Mccarthy, H., Chhetri, N. and Nicholas, K. (2015) How climate change affects extremes in maize and wheat yield in two cropping regions. *American Meteorological Society*, 28, 4653–4687.

Urban, D., Sheffield, J. and Lobell, D. (2015) The impacts of future climate and carbon dioxide changes on the average and variability of US maize yields under two emission scenarios. *Environmental Research Letters*, 10(4), 045003.

Vogel, E., Donat, M., Alexander, L., Meinshausen, M. and Frieler, K. (2019) The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14(5), 054010.

Wang, E., Martre, P., Zhao, Z., Ewert, F., Maiorano, A., Rötter, R.P., Kimball, B.A., Ottman, M.J., Wall, G.W., White, J.W., Reynolds, M.P., Alderman, p.D., Aggarwal, p.K., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A.J., de Sanctis, G., Doltra, J., Dumont, B., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Koehler, A.K., Liu, L., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ripoche, D., Ruane, A.C., Semenov, M.A., Shcherbak, I., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wallach, D., Wang, Z., Wolf, J., Zhu, Y. and Asseng, S. (2017) The uncertainty of crop yield projections is reduced by improved temperature response functions. *Nature Plants*, 3(8), 17102.

Wheeler, T. and Joachim, B. (2013) Climate change impacts on global food security. *Science*, 341, 508–513.

Welch, J., Vincent, J., Auffhammer, M., Moya, P., Dobermann, A. and Dawe, D. (2010) Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, 107(33), 14562–14567.

Xiao, D., Liu, D., Wang, B., Feng, P., Bai, H. and Tang, J. (2020) Climate change impact on yields and water use of wheat and maize in the north China plain under future climate change scenarios. *Agricultural Water Management*, 238(106238), 1–15.

Zampieri, M., Ceglar, A., Dentener, F. and Toreti, A. (2017) Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters*, 12(6), 064008.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A.C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z. and Asseng, S. (2017) Temperature increase reduces global yields ofmajor crops in four independent estimates. *Proceedings of the National Academy of Sciences of the USA*, 114(35), 9326–9331.

Zipper, S.C., Qiu, J. and Kucharik, C. (2016) Drought effects on US maize and soybean production: spatiotemporal patterns and historical changes. *Environmental Research Letters*, 11(9), 094021.

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