Soil indigenous nutrients increase the resilience of maize yield to climatic warming in China

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Abstract
Climate warming leads to crop yield loss. Although investigations have shown the region-specific effect of climate warming on maize yield in China, the determinants of this region-specific effect are poorly known. Using county-level data from 1980 to 2010 for China, we investigated the dependence of yield change under climate warming on soil indigenous nutrients. Analysis of the data indicated an average decrease of 2.6% in maize yield for 1 °C warming. Warming-related yield loss occurred mostly in western China, the North China Plain, and the southwest region of Northeast China. By contrast, climate warming did not decline maize yield in the northern region of Northeast China, south, and southwest China. Summer maize is more sensitive to warming than spring maize. A 1 °C warming resulted in an average loss of 3.3% for summer maize and 1.8% for spring maize. The region-specific change in yield can be well quantified by a combination of soil indigenous total nitrogen (STN), available phosphorus (SAP), and available potassium (SAK). Under climate warming, maize yields in regions with high STN generally increased, while the risk of yield reduction appeared in regions with high SAK. Areas that were vulnerable (defined as a yield loss higher than 1% for a 1 °C increase) to climate warming accounted for 62%, while areas that showed resilience (defined as a yield increase higher than 1% for a 1 °C increase) to climate warming accounted for 27% of the planting area. An increase in nitrogen fertilizer application is expected to reduce the risk of yield reduction in regions with low STN. Our findings highlight soil resilience to climate warming and underline the practice of fertilizer management to mitigate yield loss due to climate warming.

1. Introduction

China provides the world’s second largest maize production with the largest planting area (FAOSTAT 2020). Since 1980, maize production and planting area in China has been increasing by 5.43 million tons and 0.69 million hectares per year, respectively (National Bureau of Statistics of China, http://data.stats.gov.cn/). With climate change, the frequency and intensity of extreme heat and drought have been increasing in China (Chen and Sun 2015, Sun et al 2014a), which have caused severe losses in maize yield (Feng et al 2019, Kim et al 2019, Leng and Hall 2019). Approximately 42% of the yield variability was explained by climate variability over the period 1979–2008 (Ray et al 2015). Future warming of 2 °C lead to a 10% maize yield reduction in China (Tigchelaar et al 2018). Understanding the impacts of climate variables on maize yield and seeking proper adaptations is essential to cope with climate change and maintain food security.

Numerous studies have assessed the impact of climate change on maize yield by building statistical models (Tigchelaar et al 2018, Leng et al 2019). Based on county-level data, the increased temperature in growing-season from 1980 to 2008 caused an average loss of 5.8% in maize yield across China (Zhang and Huang 2013). Changes in temperature showed
a stronger influence on the yield than changes in precipitation (Loebell et al 2011, Deng et al 2019, Vogel et al 2019). The results of the model ensemble showed that maize yield would decrease by 8.0% for 1 °C warming in China (Zhao et al 2017).

Soil nutrients are crucial resources for maize growth and development. Soils with higher indigenous nutrients not only produced higher maize yield without fertilization (Xu et al 2018, Zhou et al 2019), but also improved the stability of maize yield under fertilization (Xu et al 2018). The response of maize yield to nitrogen, phosphorus, and potassium application increased with the decrease in soil indigenous nutrients (Xu et al 2014). The supply of nitrogen, phosphorus, and potassium fertilizers can significantly increase maize yield under different RCPs (Representative Concentration Pathways; IPCC 2013) (Zhang et al 2016). Maize in China was observed to be limited by nutrient availability (Mueller et al 2012). Optimized soil nutrient management effectively enhances resilience to climate change and closes the yield gap (Song et al 2015, Széles et al 2018).

Although the overall negative effect of climate change is widely detected (Gaupp et al 2020), local differences in the response of maize yield to climate change suggests extensive spatial heterogeneity (Ray et al 2015). Climate trends during the maize growth period reduced maize yield by 13.2–17.3% in southwestern China, but increased yield by 12.9–14.4% in northwestern China (Tao et al 2016). However, the causes of the spatial pattern have not been fully investigated. Field warming experiments have shown that a higher nitrogen supply increases crop yield under heat stress (Ordóñez et al 2015, Elia et al 2018). Great spatial variation exists in soil indigenous nutrients and in fertilizer application (Liu et al 2010, He et al 2015, Ma et al 2016), which likely explains the spatial pattern of maize yield change. However, the role of soil indigenous nutrients in regulating the impacts of warming on maize yield remains poorly understood.

We hypothesized that spatially uneven soil indigenous nutrients can help interpret the region-specific response of maize yield to warming, and optimized soil indigenous nutrients can increase the resilience of maize yield to cope with the negative impact of warming. We built the yield-climate relationship for each county using a multiple regression model. The larger the area of cropland, the more sampling sites. The values of soil indigenous nutrients in each site were averaged for each county. We then interpolated the station level data to a raster surface by using ArcGIS to obtain the sowing and maturity dates for each county (figure S1 (available online at stacks.iop.org/ERL/15/094047/mmedia)). Maize was divided into spring maize and summer maize according to the sowing dates (figure S2). We used crop calendar data to compute cumulative or average values in the maize growing season for each climate variable.

Climate data were extracted from the AgMERRA dataset (Ruane et al 2015). AgMERRA comprises gridded daily climate data at 0.25° spatial resolution over the period 1980–2010. Gridded daily climate variables were averaged for each county by its boundary. Mean temperature (T), total precipitation (P), and average solar radiation (R) of the maize growing season over the period 1980–2010 were then calculated for each county.

We used data on soil indigenous nutrients from the Basic Nutrients Dataset of Soil Testing and Fertilization Recommendation (NATESC 2015) to measure the relationship between yield change caused by elevated temperatures and soil. The data cover the field observations from 2563 counties. Soil was sampled at 120–8500 sites in each county, depending on the area of cropland in a given county. The larger the area of cropland, the more sampling sites. The values of soil indigenous nutrients in each county are the average of the measurements at different sites. The soil indigenous nutrients include total nitrogen (STN), available phosphorus (SAP), and available potassium (SAK). For counties without soil indigenous nutrient data, we used the comprehensive gridded soil characteristics dataset of China (Wei et al 2013).

A summary of the variables and the abbreviation used in this paper are presented in table 1.

2.2. Identification of climate effects on maize yield

Linear regression models were used to assess the climate and yield trends from 1980 to 2010 for each county. Only the significant trends were considered (p < 0.05). We averaged county-level trends into provincial level.
The impact of climate variables on maize yield was estimated using a multiple regression model (equation (1)) for 1767 counties. This approach was used in accordance with previous studies (Schlenker and Lobell 2010, Zhu et al 2019).

\[
\ln(Y_{i,t}) = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 T_{i,t} + \beta_4 P_{i,t} + \beta_5 R_{i,t} + \epsilon
\]

(1)

where \(\ln(Y_{i,t})\) is the natural logarithm of yield at county \(i\) in year \(t\). The quadratic time trend (\(\beta_1 t\) and \(\beta_2 t^2\)) was used to remove the effects of overall technological progress (e.g. artificial fertilization, and cultivar shift) on maize yield (Schlenker and Lobell 2010, Zhao et al 2017). The quadratic terms of \(T\) and \(P\) simulate the nonlinear response of yield to temperature and precipitation change, respectively. \(R\) represents the average radiation during the maize growing season. \(\epsilon\) is the model error.

The temperature sensitivity of maize yield (equation (2)) was measured by the partial derivative of equation (1) (Chen et al 2017, Zhu et al 2019).

\[
S_{Y,T} = \frac{\partial Y}{\partial T} = 100\% = (\beta_3 + 2\beta_4 T_{\text{avg}}) 100\%
\]

(2)

where \(T_{\text{avg}}\) represents the mean of \(T\) during the period 1980–2010 in county \(i\). \(\beta_3\) and \(\beta_4\) are the parameters of county \(i\) in equation (1). \(S_{Y,T}\) is the temperature sensitivity of maize yield, representing the yield change (%) for 1 °C warming. We evaluated the \(S_{Y,T}\) of 1767 counties using equations (1) and (2).

No significant trends in precipitation were detected in most of the meteorological stations and regions of China (Zhang et al 2011, Sun et al 2014b). Therefore, we did not consider the yield sensitivity to precipitation.

2.3. Quantification of the relationship between temperature sensitivity and soil indigenous nutrients

We employed a machine learning method, random forest (Breiman 2001), to evaluate the relationship between temperature sensitivity and soil indigenous nutrients. The package ‘randomForest’ (Liaw and Wiener 2002) that was built for R language was used on the input data with the control parameters \(\text{ntree} = 500\) (appropriate number of trees to ensure the model has stable and low error rates) and \(\text{mtry} = 1\) (default number of variables considered for splitting) in our study. In each tree, 36% of samples are left out and these are called out-of-bag (OOB) data. The OOB data are used to estimate the generalization error. The importance of a variable is interpreted as an increase in the mean square error (IncMSE; %) due to random permutation of that variable. The dependent variables were \(S_{Y,T}\) and the independent variables were STN, SAP, and SAK. We conducted the Random Forest algorithm for both spring maize and summer maize. We used 1767 samples to build the random forest model. For the other 477 counties without \(S_{Y,T}\), we simulated it by inputting the data on STN, SAP, and SAK into the random forest model.

3. Results

3.1. Climate and yield trends from 1980 to 2010

Warming was more pronounced than the change in precipitation and solar radiation. Significant trends in the temperature of the maize growing season were observed in 1386 counties, with an increase at the rate of 0.36 °C per decade. Large areas of northern, central, and eastern China showed positive warming trends (figure 1 (a)). For spring maize, 15 of the 22 Provinces showed significant warming trends (table S1). However, no significant warming trend was found in southwest China at the provincial scale. For summer maize, the largest warming rate was observed in Beijing (0.49 °C per decade). Only Shandong (SD) and Yunnan Provinces had no significant warming trend.

Only 218 counties showed significant trends in precipitation at an average increase rate of 28.4 mm per decade. Positive trends were found in parts of northeastern China, while negative trends were found in a narrow part of eastern and southwestern China (figure 1 (b)). At the provincial level, Heilongjiang (HLJ) Province significantly became drier (−24.0 mm per decade) during the spring maize growing season, and Gansu (GS, −40.1 mm per decade) and Sichuan (−42.2 mm per decade) Provinces

| Abbrev. | Variable description |
|--------|----------------------|
| \(Y\)  | Maize yield (kg ha\(^{-1}\)) |
| \(t\)  | Time in years        |
| \(T\)  | Mean temperature during growing season of maize (°C) |
| \(P\)  | Total precipitation during growing season of maize (mm) |
| \(R\)  | Mean solar radiation during growing season of maize (MJ m\(^{-2}\) d\(^{-1}\)) |
| STN    | Soil total nitrogen (g kg\(^{-1}\)) |
| SAP    | Soil available phosphorus (mg kg\(^{-1}\)) |
| SAK    | Soil available potassium (mg kg\(^{-1}\)) |
| \(S_{Y,T}\) | Temperature sensitivity of maize yield (% per °C) |

Table 1. Target variables and features used in this study.
became drier during the summer maize growing season (table S1). However, precipitation increased by 50.8 mm per decade in SD Province.

Downward trends in solar radiation occurred in a part of northwestern, southwestern, and eastern China, while upward trends occurred in a confined area of central China (figure 1(c)). The average trend of 280 counties was $-0.32 \text{ MJ m}^{-2} \text{ d}^{-1}$ per decade. For spring maize, solar radiation significantly decreased in Ningxia (NX) and GS Provinces (table S1). For summer maize, Xinjiang (XJ) was the only Province with a reduced rate in solar radiation.

Maize yield in China has been constantly increasing over the past decades. Significant trends were observed in 1570 counties (89% of maize growing counties) at an average increase rate of 120.4 kg ha$^{-1}$ yr$^{-1}$. Positive trends (1559 counties) occurred extensively in maize planting areas, especially in northeastern and northwestern China (figure 1(d)). Remarkable enhancements were found in XJ (237.4 kg ha$^{-1}$ yr$^{-1}$), HLJ (167.8 kg ha$^{-1}$ yr$^{-1}$), NX (155.9 kg ha$^{-1}$ yr$^{-1}$), Jilin (JL, 153.4 kg ha$^{-1}$ yr$^{-1}$), and Inner Mongolia (IM, 153.0 kg ha$^{-1}$ yr$^{-1}$) Provinces. Another 17 Provinces recorded an increased yield of 100–140 kg ha$^{-1}$ yr$^{-1}$. Spring maize (124.3 kg ha$^{-1}$ yr$^{-1}$) had stronger elevated trends in yield than summer maize (113.1 kg ha$^{-1}$ yr$^{-1}$).

### 3.2. Temperature sensitivity of maize yield

Figure 2 shows the distributions of $S_{YT}$ of spring maize (figure 2(a)) and summer maize (figure 2(b)) simulated by equations (1) and (2). The change in yield was concentrated in ±20% for 1 °C warming for both spring maize and summer maize. The area weighted average yield of spring maize in 1077 counties and summer maize in 690 counties decreased by 1.1% and 2.9% for 1 °C warming, respectively. Summer maize is more vulnerable than spring maize. $S_{YT}$ showed a clear spatial pattern. The positive impacts of increased temperature were distributed in the northern areas of Northeast, Central, and South China, and the negative impacts mainly occurred in the southern areas of Northeast China, Loess Plateau, and North China Plain (figure S3).

### 3.3. Relationship between $S_{YT}$ and soil indigenous nutrients

The random forest model was built with data from 1767 counties. It revealed that STN was the most important predictor of $S_{YT}$ for spring maize (IncMSE = 40.2%), followed by SAK.
(IncMSE = 17.7%) and SAP (IncMSE = 16.8%). The most important predictor for summer maize was SAK, followed by STN and SAP, and their IncMSEs were 12.8, 5.9, and 2.2%, respectively. The $R^2$ of the model was 0.78 for spring maize and 0.73 for summer maize. The high $R^2$ indicated that the soil indigenous nutrients regulated the response of maize yield to temperature increase and explained the spatial pattern of $S_{Y,T}$ well.

The partial dependence plots visualized the relationship between $S_{Y,T}$ and soil indigenous nutrients (figure 3). Most of STN (95%) of spring maize and summer maize were concentrated from 0.52 to 2.52 and from 0.61 to 2.14 g kg$^{-1}$, respectively. With the increase of STN, the response of spring maize yield to warming changed from negative (yield loss) to positive (yield increase) (figure 3(a)), while summer maize did not show a consistent dependency (figure 3(d)). In agreement with the order of IncMSE, SAP also did not show a consistent dependency (figures 3(b) and (e)). SAK of spring maize and summer maize were mainly distributed from 88.9 to 93.7 and from 74.1 to 197.7 mg kg$^{-1}$, respectively. As SAK increase, the risk of yield loss increased in a certain range of SAK (figures 3(c) and (f)).

We calculated the $S_{Y,T}$ of an additional 477 counties that had less than 20 years of records through the random forest model. Compared to $S_{Y,T}$ simulated by climate variables (figure 2), $S_{Y,T}$ simulated by soil indigenous nutrients was distributed in a narrower interval (figure 4). Counties with $S_{Y,T}$ between ±10% account for 89% and 90% of the total for spring maize and summer maize, respectively (figure 4). The average yield losses of spring maize and summer maize were 1.8% and 3.3% for 1 $^\circ$C warming, respectively. For all maize planting areas, 751 counties showed a positive response to warming (3.8% $^\circ$C$^{-1}$), but 1493 counties showed negative responses (−5.8% $^\circ$C$^{-1}$). The area-weighted average maize yield in 2244 counties decreased by 2.6% for 1 $^\circ$C warming. Based on the average of the provincial scale, maize yield in 25 of the 31 Provinces decreased with increasing temperature (table S2).

### 3.4. Spatial distribution of soil indigenous nutrients and $S_{Y,T}$

Great variation in soil indigenous nutrients existed across different regions (figure 5). Northeastern and southwestern China showed higher STN content (figure 5(a)). The STN of HLJ, JL, Tibet, and Guizhou Provinces exceeded 2.00 g kg$^{-1}$ (table S2). However, the STN of northwestern China and the North China Plain was lower, even less than 1.00 g kg$^{-1}$ in Shanxi (SX), Shaanxi, NX, SD, Henan, and Hebei Provinces. High SAP content was seen in northeastern, southwestern China, and North China Plain (figure 5(b)). SD and SX Provinces showed the highest (26.8 mg kg$^{-1}$) and lowest (12.5 mg kg$^{-1}$) SAP content, respectively. SAK content was higher in northern China than in southern China (figure 5(c)). Most Provinces in the south showed less than 100 mg kg$^{-1}$ of SAK, while in the north, values over 120 mg kg$^{-1}$ of SAK were seen (table S2).

We built a framework to measure the capability of soil indigenous nutrients to mitigate the impact of warming on maize yield. We classified different effects of soil indigenous nutrients on $S_{Y,T}$ into seven levels: extreme vulnerability ($S_{Y,T} \leq −10\%$ per $^\circ$C), moderate vulnerability ($−10\%$ per $^\circ$C $< S_{Y,T} \leq −5\%$ per $^\circ$C), low vulnerability ($−5\%$ per $^\circ$C $< S_{Y,T} \leq −1\%$ per $^\circ$C), marginal ($−1\%$ per $^\circ$C $< S_{Y,T} \leq 1\%$ per $^\circ$C), low resilience (1% per $^\circ$C $< S_{Y,T} \leq 5\%$ per $^\circ$C), moderate resilience (5% per $^\circ$C $< S_{Y,T} \leq 10\%$ per $^\circ$C), and high resilience ($S_{Y,T} > 10\%$ per $^\circ$C). The areas of extreme vulnerability were mainly distributed in the Loess Plateau (figure 5(d)). The areas of moderate and low vulnerability were concentrated in the XI and IM Provinces,
Figure 3. Partial dependence plots for (a), (d) STN, (b), (e) SAP, and (c), (f) SAK. The figures show the average deviation in temperature sensitivity (\(S_{Y,T}\); % °C\(^{-1}\)) caused by a given variable. The dense short lines on x-axis indicate that most of the data are distributed here. The red and blue lines represent the results of spring maize and summer maize, respectively.

Figure 4. Frequency distributions of \(S_{Y,T}\) (% per °C) simulated by soil indigenous nutrients. (a) Spring maize planted in 1457 counties and (b) summer maize planted in 787 counties. The red line represents the frequency fitted by the amplitude version of the Gaussian peak function.

North China Plain, and in the southern regions of Northeast China. Resilience mainly occurred in the IM, Hunan, Guangxi Provinces, northern regions of Northeast China, and the western part of Southwest China. The spatial distribution of \(S_{Y,T}\) resembled that of STN.

In the context of climate warming, maize yields in regions with high STN generally increased, while the risk of yield reduction appeared in the regions with high SAK (table S2). In addition, the SAP concentration is likely not closely related to the warming-related yield change (table S2).

3.5. Increased resilience of maize yield via soil indigenous nutrients

Summer maize is more vulnerable to climate warming than spring maize. The vulnerable area of summer maize and spring maize were 8.47 Mha and 7.97 Mha, respectively, accounting for 72.1% and 53.6% of the total planting area (figure S4). The areas of summer and spring maize with resilience accounted for 15.9% and 36.1%, respectively. Overall, the vulnerable area and the resilience area accounted for 62% and 27% of the total maize-planted area in China.
Figure 5. Spatial distribution of soil indigenous nutrients and \( S_{YT} \). Colored areas represent different gradients of STN (a), SAP (b), and SAK (c). Seven colors represent different effects of soil indigenous nutrients on \( S_{YT} \) (d), that is, \( S_{YT} \leq -10\% \) per \(^\circ\)C, extreme vulnerability; \(-10\% < S_{YT} \leq -5\% \) per \(^\circ\)C, moderate vulnerability; \(-5\% < S_{YT} \leq -1\% \) per \(^\circ\)C, low vulnerability; \(-1\% < S_{YT} \leq 1\% \) per \(^\circ\)C, marginal; \( 1\% < S_{YT} \leq 5\% \) per \(^\circ\)C, low resilience; \( 5\% < S_{YT} \leq 10\% \) per \(^\circ\)C, moderate resilience; \( S_{YT} > 10\% \) per \(^\circ\)C, high resilience.

We averaged the STN, SAP, and SAK for each level of \( S_{YT} \) to obtain more insights into what kind of soil indigenous nutrient conditions increase the resilience of maize yield (table 2). \( S_{YT} \) of spring maize increased with increases in STN and SAP. The yields decreased by more than 10\% per \(^\circ\)C in regions where STN and SAP were less than 0.91 g kg\(^{-1}\) and 13.4 mg kg\(^{-1}\), respectively. In regions where STN exceeded 1.80 g kg\(^{-1}\) and SAP exceeded 19.6 mg kg\(^{-1}\), spring maize showed resilience to the impacts of warming. STN and SAP in maize planting areas with high resilience to warming were twice as high as in areas that were extremely vulnerable to warming. About 31\% of the 1457 counties were resilient to the negative impacts of warming because of favorable soil indigenous nutrients. In barren spring maize planting regions, the negative effects of temperature rise can be reduced and yield can be improved by increasing the application of nitrogen and phosphorus fertilizer.

\( S_{YT} \) of summer maize increased with an increase in STN (table 2). Yield decreased by more than 10\% for 1\(^\circ\)C warming in the regions with STN less than 1.10 g kg\(^{-1}\). Summer maize obtained resilience to warming in regions with an STN of more than 1.33 g kg\(^{-1}\). However, only 18\% of the 787 counties were resilient for temperature rise because of appropriate soil indigenous nutrients. Maize yield benefitted from a relatively low SAK. Increasing the use of nitrogen fertilizer and appropriately decreasing potassium fertilizer can increase the resilience of summer maize against the negative impacts of elevated temperature.

4. Discussion

Temperature is the predominant factor affecting maize yield (Lobell et al 2011). Our study revealed that for each degree Celsius increase in mean temperature, the area-weighted average maize yield was reduced by 2.6\%. From a physiological perspective, the inhibitory effect of high temperature on leaf photosynthesis was associated with the reduction of Rubisco activase activity (Crafts-Brandner and Salvucci 2000, 2002). High temperature also restrains the duration of light capture, radiation use efficiency, and harvest index (Cicchino et al 2010, Edreira and Otegui 2012). Heat stress, especially at anthesis and grain filling phases, reduced pollen viability, kernel number, and individual kernel mass (Cárcova and Otegui 2001, Lizaso et al 2018). The comprehensive negative influences of warming ultimately lead to yield losses.

However, the results of our study revealed the positive impacts of warming on maize yield
in northeastern, central, and southwestern China (figure 5(d)), which implied effective adaptation of those regions against warming. Suitable soil indigenous nutrients, especially higher nitrogen contents, were demonstrated to provide resilience for maize to cope with warming (table 2). Field experiments revealed that high-nitrogen maize plants possess higher values of maximum photosynthetic rate and accumulate more plant biomass than low-nitrogen maize plants (Zhao et al. 2003). Furthermore, high-nitrogen maize plants are inclined to allocate a greater proportion of biomass to aboveground parts (Chen et al. 2013). Radiation use efficiency and water use efficiency also increase with the increase in nitrogen fertilizer applications (Teixeira et al. 2014). Thus, regions with higher STN can increase resilience to warming via these biophysical processes or response mechanisms.

Our results indicated that extensive maize planting areas were vulnerable to temperature rise (figure 5). Maize yield in 80% of the Provinces decreased with increasing temperature (table S2). SX is the most vulnerable Province with the largest yield decrease rate (−11.5% °C−1) and the lowest STN (0.82 g kg−1) and SAP (12.5 mg kg−1) content (table S2). The average application of nitrogen, phosphorus, and potassium fertilizers from 1987 to 2010 in SX Province was 108.2 kg ha−1, 52.6 kg ha−1, and 19.3 kg ha−1, respectively (National Bureau of Statistics of China, http://data.stats.gov.cn/), which is much lower than the optimal fertilization for maize to obtain high yield (Zhang et al. 2018). Under 1 °C warming, maize supplied with 200 kg N ha−1 resulted in about 14% more yield than maize that was supplied with 100 kg N ha−1 (Ordóñez et al. 2015). Therefore, the shortage of nitrogen supplies causes remarkable losses in yield when the temperature increases.

We can enhance the resilience of maize yield to the negative effects of warming by increasing the application of nitrogen fertilizers in barren areas. For instance, when the STN content in the regions of spring maize was less than 0.91 g kg−1, the yield decreased by more than 10% for 1 °C warming. If the application of nitrogen fertilizer in these regions increases the STN content to higher than 1.80 g kg−1, the maize yield can benefit from increased temperature (table 2). A five-year warming experiment conducted in Hailun County, Heilongjiang Province in Northeast China showed that maize yield increased by 11.8 ± 2.5% (mean ± SD, n = 5) for 1 °C warming (Qiao et al. 2019). STN, SAP, and SAK in this experiment were 2.21 g kg−1, 41.2 mg kg−1, and 228.9 mg kg−1, respectively (Qiao et al. 2010). Our model calculation, using the soil indigenous nutrients as input, resulted in a maize yield increase of 8.1% for 1 °C warming, which is in agreement with Qiao et al. (2019). In the barren field with 0.08 g STN kg−1, 10.5 mg SAP kg−1, and 103.9 mg SAK kg−1, the maize yield decreased by as much as 13% for 1 °C warming (Abebe et al. 2016, Mina et al. 2017). These field-warming experiments support our results that higher soil indigenous nitrogen increases the resilience of maize yield to warming.

The impacts of increased temperature on vegetation are regulated by water supply (Wang et al. 2014, Reich et al. 2018). Maize grown in extreme heat requires more water for carbon assimilation and transpiration (Lobell et al. 2013). Although the effects of precipitation (P) and temperature (T) were measured as two separate model components in our study (equation (1)), $S_{Y,T}$ was inevitably affected by $P$. We fitted the influence of $P$ on $S_{Y,T}$ (figure 6). $S_{Y,T}$ increased with the increase in $P$, that is, yield increased for 1 °C warming in the areas with higher precipitation. The slopes in figures 6(a) and (b) show that spring maize and summer maize increased by 0.8% and 0.6% per °C for a 100 mm increase in P, respectively. The slopes show that although precipitation significantly affects the response of maize yield to elevated temperature, the degree of the impacts was limited.

Irrigation considerably cooled the daytime land surface temperature (Li et al. 2020, Yang et al. 2020). Therefore, irrigation can lower the temperature sensitivity of maize and mitigate the effects of heat waves and drought events induced by water stress on maize yield (Schauberger et al. 2017, Jägermeyr and Frierer 2018). In arid and semi-arid regions of China, including IM Province, Loess Plateau, and western China, maize growth depends on irrigation to meet the water needs.
requirements. Irrigation was not taken into account in our model due to unavailable data on the area and amount of irrigation, which leads to the uncertainty of our simulations in irrigated systems. It is expected that the effect of irrigation on maize yield in the context of climate warming could be determined when detailed irrigation data are available in the future.

Another uncertainty in our study is that we did not consider elevated CO$_2$ levels. CO$_2$ fertilization increases photosynthesis and CO$_2$ enrichment enhances the water-use efficiency under water stress conditions (Ainsworth and Long 2005), which can fill the yield gaps caused by climate change. However, maize, being a C4 crop, benefits less from elevated CO$_2$ (Long et al 2006, Makowski et al 2020). The results of the model simulation suggested that elevated CO$_2$ only limitedly offsets maize yield loss (Jin et al 2017, Schaubberger et al 2017).

5. Conclusion

Climate warming in China resulted in maize yield loss generally. Warming-related yield loss occurred mostly in western China, the North China Plain, and the southwest region of Northeast China. Summer maize was more sensitive to warming than spring maize. The vulnerable area (defined as a yield loss higher than 1% for a 1 °C increase) and the resilience area (defined as a yield increase higher than 1% for a 1 °C increase) to climate warming accounted for 62% and 27% of the total maize-planted area, respectively. Soil indigenous nutrients regulated the effects of climate warming on maize yield, which can be well determined by random forest model. Higher soil indigenous nutrients increased the resilience of maize yield to climate warming. An increase in fertilization is expected to reduce the risk of yield reduction in regions with low soil indigenous nutrients.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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