# Impact assessment of heat stress during post-silking period of summer maize in the Huang-Huai-Hai Plain, China

Zhenzhen Fu, Zhijuan Liu ⓘ, Shibo Guo, Zhentao Zhang, Xiaomeng Lu, Jingjin Gong, Meiqi Dong and Xiaoguang Yang

College of Resources and Environmental Sciences, China Agricultural University, No. 2 Yuanmingyuan West Rd., Beijing 100193, China

## Abstract

Arising of disasters by climate change had affected crop growth and yield, and then threaten local to global food security, particularly heat stress. Therefore, hazard assessment is essential to develop effective disaster risk management and adaptation interventions to ensure food security. In this study, the accumulated heat stress days (DAY), heat stress intensity (HSI) and heat degree-days (HDD) during the post-silking period of summer maize in The Huang-Huai-Hai Plain were investigated. Based on the optimal probability distribution function of HDD and information diffusion theory, we compute heat stress classification index and the possibility of heat stress, respectively. During 1981–2019, DAY, HSI and HDD were 11.8 d, 31.9°C and 23.6°Cd and increased by 0.67 d/decade, 0.10°C/decade and 3.14° Cd/decade, respectively. The threshold and hazard probability of mild, moderate and severe heat stress were 9.4, 19.4 and 34.2°Cd and 16.6, 9.3 and 4.5%, respectively. The heat stress hazard index ($M$) was 0.48, ranged from 0 to 0.77 during 1981 to 2019. $M$ will increase in the future at all regions, particularly after 2060. Under SSP5-8.5 climate scenario, $M$ ranged from 0.95 to 1.20 in 2080s, about two times than historical period. This could be used in optimizing agricultural management in summer maize production in order to combat heat stress under projected climate change.

## Introduction

Maize (*Zea mays* L.) is one of the most widely planted crops in the world, accounting for approximately 37.2% of global cereal production (FAO, 2016). As increasing in global population, human consumption and animal feed, maize demand will further rise which would except to double by 2050 (CIMMYT, 2011). The production of maize depends on both planting area and yields, and meeting the increased demand will require an increased in one or both of these factors. In recent decades, maize yields have been greatly improved, which is mostly due to fertilizer applications and irrigation (Zhou *et al.*, 2019; Yu *et al.*, 2022). However, climate change has led to disasters such as droughts, floods and extreme temperature events that cause significant damage to crop growth and yield, posing a threat to local and global food security (Corey *et al.*, 2016; Schmitt *et al.*, 2022; Rohde, 2023). Therefore, timely and robust scientific information is essential to develop effective disaster risk management strategies and prevent damages to ensure global food security.

Meteorological disasters, particularly heat stress, are the primary contributors to the fluctuation of maize production under climate change (Zhao *et al.*, 2017; Lizaso *et al.*, 2018; El-Sappah *et al.*, 2022). From 2001 to 2020, the global average temperature was estimated to have reached 0.84–1.10°C higher values than the period from 1850 to 1990 (IPCC, 2021). The global rise in surface temperature will result in increased frequency, duration and the magnitude of extreme high temperature events (Huo *et al.*, 2023; IPCC, 2023). Since the 1980s, China's surface temperature increased and was greater at higher northern latitudes (Liu, 2018; Huo *et al.*, 2023). These changes will have considerable impacts on agricultural production (Lobell *et al.*, 2011; Wang *et al.*, 2014).

The Huang-Huai-Hai (HHH) Plain, located in eastern China, accounted for 32 and 34% of the maize planting area and maize production in China, respectively (Liu, 2012). The planting area and yield of maize in this region increased during the past decades (Xue *et al.*, 2016; Jiang *et al.*, 2018). However, the rising summer temperatures (Gao *et al.*, 2009) have led to an increase in the frequency and intensity of heat stress during the critical period of summer maize (Wang *et al.*, 2018), which will lead to an increasing risk of heat stress during the critical period of summer maize (Zhang *et al.*, 2018b; Zhang *et al.*, 2021a). The post-silking period (PSP) is the sensitive period to heat stress, which is critical to maize kernel dry matter

accumulation and yield formation (Lizaso *et al.*, 2018; Wang *et al.*, 2021). During this period, heat stress can cause the pollensterilization, reduce the grain-filling rate, shorten the duration of the period, lower the kernel weight (Mayer *et al.*, 2014; Wang *et al.*, 2021), resulting in a significant yield loss (Yang *et al.*, 2017; Zhang *et al.*, 2017). For each 1°C increase, the yield decreases by 2.4% (Lu *et al.*, 2015). Therefore, understanding the hazard of heat stress during the PSP of summer maize is crucial for defending against heat stress damage, managing production and reducing economic losses in agricultural production.

However, there were few studies focused on the hazard of heat stress during the PSP of maize (Couëdel *et al.*, 2021; Gao *et al.*, 2021). Moreover, there is no clear threshold for classification of heat stress during the PSP of maize. Therefore, the objectives of this study are to: (i) investigate the long-term variation trends of accumulated heat stress days (DAY), heat stress intensity (HSI) and heat degree-days (HDD) during the PSP of summer maize; (ii) to construct the index of classification for heat stress in the PSP of summer maize; and (iii) to assess the hazard of heat stress in the PSP of summer maize in the historical period (1981–2019) and future period (2020–2100).

## Materials and methods

### Research area

This study was conducted in the HHH Plain of China, including four sub-regions: Beijing-Tianjin-Hebei region (Jing-Jin-Ji, JJJ), Shandong province (SD), Henan province (HN) and parts of Anhui and Jiangsu province (Su-Wan, SW) (Fig. 1a). This region belongs to East Asian Temperate Monsoon Climate zone. During the maize growing season (From June to September), the mean maximum temperature ranged from 22.9 to 35.0°C, the mean minimum temperature ranged from 12.3 to 26.2°C; the total precipitation ranged from 345 to 1015 mm, and the average solar radiation per day ranged from 20.6 to 25.3 MJ/m$^2$ (Tian, 2016; Zheng *et al.*, 2022). The main cropping system is double cropping, which is dominated by winter wheat and summer maize rotation (Zhang *et al.*, 2022).

### Climate and crop data

In this study, 64 weather stations were selected from the National Meteorological Networks of the China Meteorological Administration (CMA) (Fig. 1a). Climate data included daily maximum temperatures from 1981 to 2019 at each station.
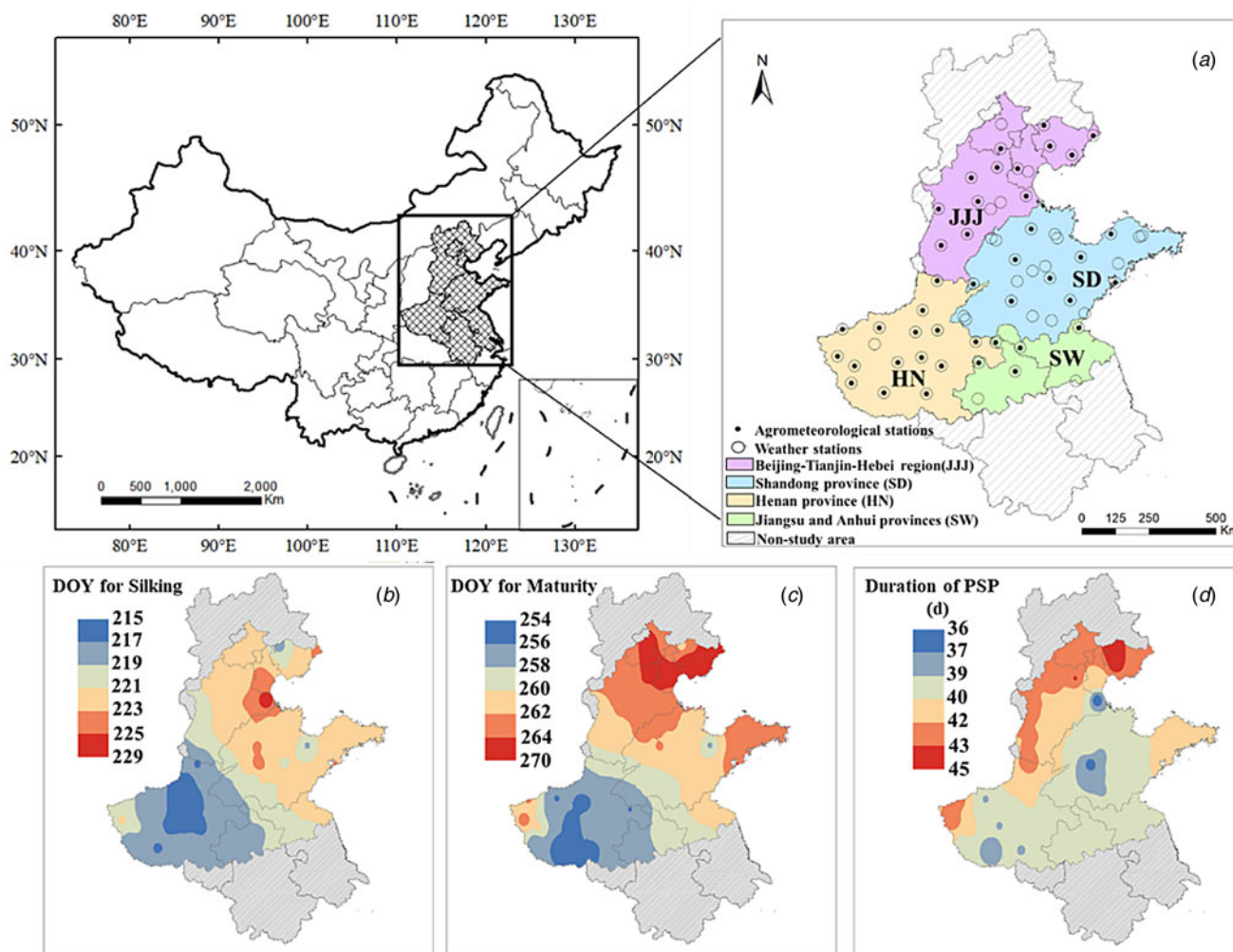


**Figure 1.** (a) The locations selected in the Huang-Huai-Hai Plain in China. Lines show province boundaries. Sub-regions are named in italic. (b) and (c) are the averages of DOY (day of year) for silking and maturity dates and (d) is the duration of post-silking period (PSP, from silking to maturity).

Projected daily maximum temperature data were selected from Sixth Coupled Model Intercomparison Project (CMIP6; https://esgf-node.llnl.gov/projects/cmip6/) (with the resolution of 0.5° × 0.5°), under three SSP scenarios (SSP1–2.6, SSP3–7.0 and SSP5–8.5) in two time periods of the 21st century: the 2040s (2020–2060) and the 2080s (2061–2100). We selected five GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1.2-HR, MRI-ESM2.0, UKESM1.0-LL). The observational reference dataset used for bias adjustment and statistical downscaling in the above data is version 2.0 of WFDE5 over land merged with ERA5 over the ocean (W5E5) (Cucchi *et al.*, 2020; Lange *et al.*, 2021). This dataset covers 1979–2019 at daily temporal resolution and the entire globe at 0.5° spatial resolution. The algorithm has been adjusted and improved on the basis of version 1.0 to avoid the occurrence of excessive daily maximum temperature values in some grid cells in some months, making it closer to historical climate data. The original climate scenario data were extracted from the Intersectoral Impact Model Intercomparison Project (ISI-MIP, https://data.isimip.org/search/). The maize phenology data, including silking and maturity dates, were obtained from 42 agricultural meteorological experiment stations (Wu *et al.*, 2021; Tao *et al.*, 2022). The observations of above have uniform CMA observing standards and guidelines (Liu *et al.*, 2013).

We referred to the period from silking to maturity as the PSP. According to the decadal averages of silking and maturity dates of PSP (Table 1), there was little changes after 2000, therefore, we used the silking and maturity dates in 2013 to fill up the missing records after 2013. The inverse distance weighted interpolation method was used to interpolate the phenology data from agricultural meteorological experiment stations to entire research area. Then we extracted the phenology data for the 64 weather stations according to the latitude and longitude (Figs 1b–d).

### *Methodology to hazard assessment of heat stress*

Three steps are included in the framework for hazard assessment of heat stress (Fig. 2).

Step 1. Selecting the heat stress indices.

To comprehensively evaluate the occurrence and impact of heat stress during the PSP of summer maize, three heat stress indices were developed, including HSI, accumulated heat stress days (DAY) and HDD. These indices were based on daily maximum temperature during the PSP. DAY is the number of days with $T_{max,i} \geqslant 30°C$, calculated with Eqns (1) and (2) (Schauberger, *et al.*, 2017). HSI is the average of daily maximum temperature for days when $T_{max,i} \geqslant 30°C$. HDD is the total HDD

during the PSP considered the frequency, duration and intensity of heat stress, calculated with Eqns (3) and (4) (Shimono, 2011).

$$DAY = \sum_{d_s}^{d_m} DAY_i \qquad (1)$$

$$DAY_i = \begin{cases} 1 & T_{max,i} \geq T_h \\ 0 & T_{max,i} < T_h \end{cases} \qquad (2)$$

$$HDD = \sum_{d_s}^{d_m} HD_i \qquad (3)$$

$$HD_i = \begin{cases} T_{max,i} - T_h & T_{max,i} \geq T_h \\ 0 & T_{max,i} < T_h \end{cases} \qquad (4)$$

where $d_s$ is the silking date; $d_m$ is the maturity date; $T_h$ is the threshold temperature for heat stress of maize (30°C); $T_{max,i}$ is daily maximum temperature on day $i$ (CMA, 2008; Lobell *et al.*, 2013).

Step 2. Constructing the index of classification for heat stress.

Five types of probability distribution models (Normal, Exponential, Weibull, Cauchy and Poisson) were used to fit the probability distribution curve of HDD at each site, which shown in Eqns (5)–(9) (Huo and Jiang, 2006; Yang *et al.*, 2020). The maximum likelihood estimation method was used to estimate the parameters in the model. Then optimal probability distribution function was selected based on the Kolmogorov–Smirnov method (K-S) at each site.

$$\text{Normal distribution:} f(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (5)$$

$$\text{Exponential distribution:} f(x|\mu) = \frac{1}{\mu} e^{-\frac{x}{\mu}} \qquad (6)$$

$$\text{Weibull distribution:} f(x|a, b) = abx^{b-1} e^{-ax^b} \qquad (7)$$

$$\text{Cauchy distribution:} f(x|\gamma, x_0) = \frac{1}{\pi}\left[\frac{\gamma}{(x - x_0)^2 + \gamma^2}\right] \qquad (8)$$

$$\text{Poisson distribution:} f(x|\lambda) = \frac{e^{-\lambda} \lambda^x}{x!} \qquad (9)$$

**Table 1.** Averages of silking and maturity dates and the duration of post-silking period (silking to maturity) of summer maize in the four sub-regions during 1981–2019

| | Silking date (DOY) | | | | Maturity date (DOY) | | | | Duration (d) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | JJJ | SD | HN | SW | JJJ | SD | HN | SW | JJJ | SD | HN | SW |
| 1980s | 215 | 221 | 219 | 221 | 255 | 256 | 255 | 256 | 41 | 36 | 37 | 36 |
| 1990s | 223 | 221 | 220 | 221 | 264 | 261 | 260 | 261 | 42 | 41 | 41 | 41 |
| 2000s | 227 | 225 | 218 | 221 | 269 | 265 | 260 | 261 | 43 | 41 | 43 | 41 |
| 2010s | 227 | 223 | 217 | 218 | 270 | 265 | 257 | 259 | 44 | 43 | 41 | 42 |
| 1981–2019 | 223 | 223 | 218 | 220 | 264 | 262 | 258 | 259 | 42 | 40 | 41 | 40 |

*JJJ, Beijing-Tianjin-Hebei region; SD, Shandong province; HN, Henan province; SW, Jiangsu and Anhui provinces.
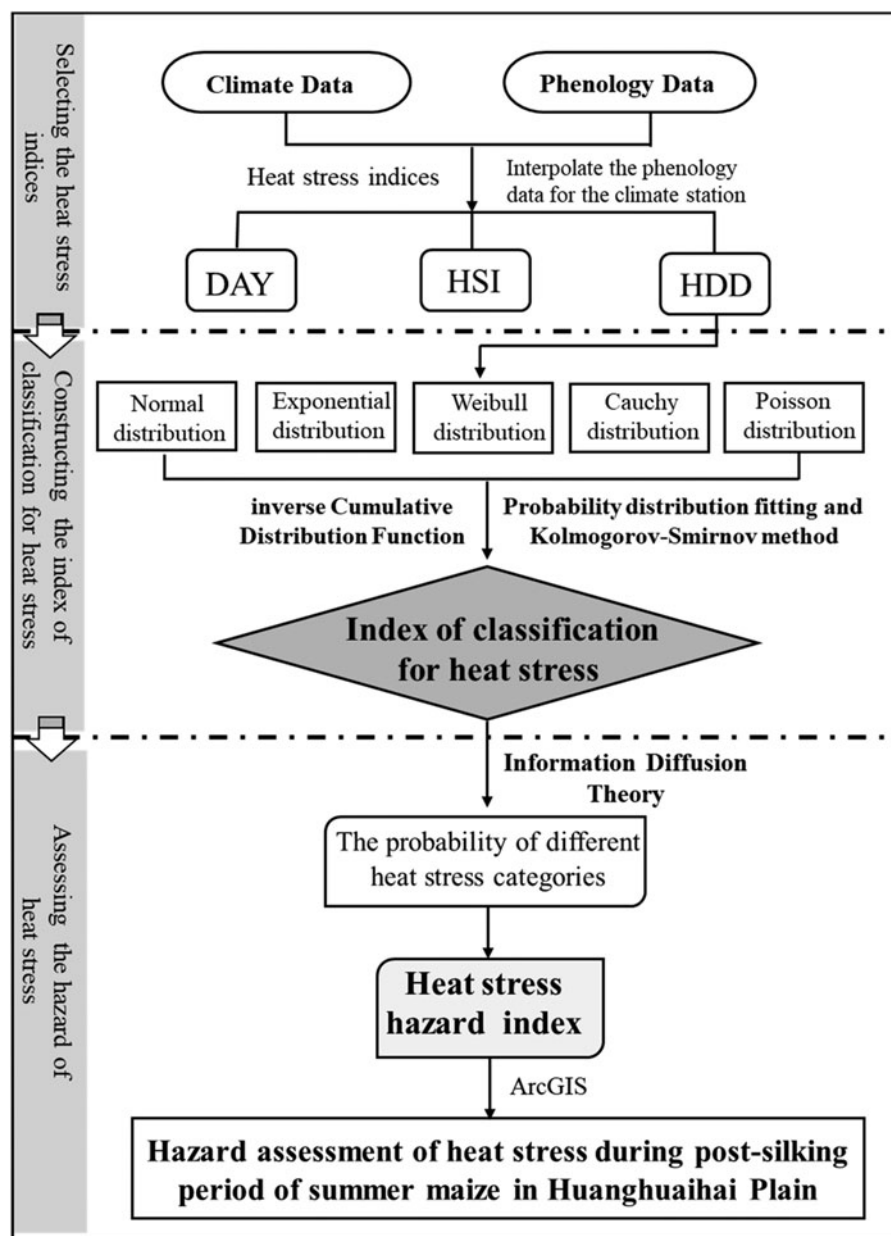
**Figure 2.** Flow chart showing the procedure used to make hazard assessment of heat stress to summer maize during the post-silking period. DAY, accumulated heat stress days; HSI, heat stress intensity; HDD, heat degree-days.

Based on HDD optimal probability distribution function, the inverse Cumulative Distribution Function (iCDF) was used to determine the threshold of different heat stress categories. Referring to Yang *et al.* (2021), iCDF (0.25), iCDF (0.50) and iCDF (0.75) were taken as the lower limit of mild, moderate and severe heat stress. Therefore, the classification of heat stress intensities based on the range of HDD values was made into three different heat stress categories.

Step 3. Accessing the hazard of heat stress.

Based on established index for different heat stress categories, the information diffusion theory (Huang, 2005) was used to calculate the possibility ($P_i$) of heat stress in level $i$ to assess the hazard of different heat stress categories. The information diffusion theory has been widely used in disaster risk assessment and allowed for more accuracy in risk estimation (Hao *et al.*, 2012; Liu *et al.*, 2019).

Considering the probability and intensity of different heat stress categories, the heat stress hazard index ($M$) is constructed

as follows:

$$M = \sum_{i=1}^{n} P_i Q_i \tag{10}$$

where $n$ is the disaster intensities, $n = 3$; $Q_i$ is the weight of intensity for each level, that is, the weights of mild, moderate and severe level were 1, 2 and 3, respectively (Yang *et al.*, 2021); $P_i$ is the possibility of heat stress for summer maize in level $i$, which is calculated by information diffusion theory.

## Results

### Spatial variation of heat stress during post-silking period

At the regional scale, we found the average DAY, HSI and HDD in the HHH Plain was 11.8 d (3–17 d), 31.9°C (31.2–32.7°C) and 23.6°Cd (4.4–46.0°Cd) during 1981 to 2019, respectively. There
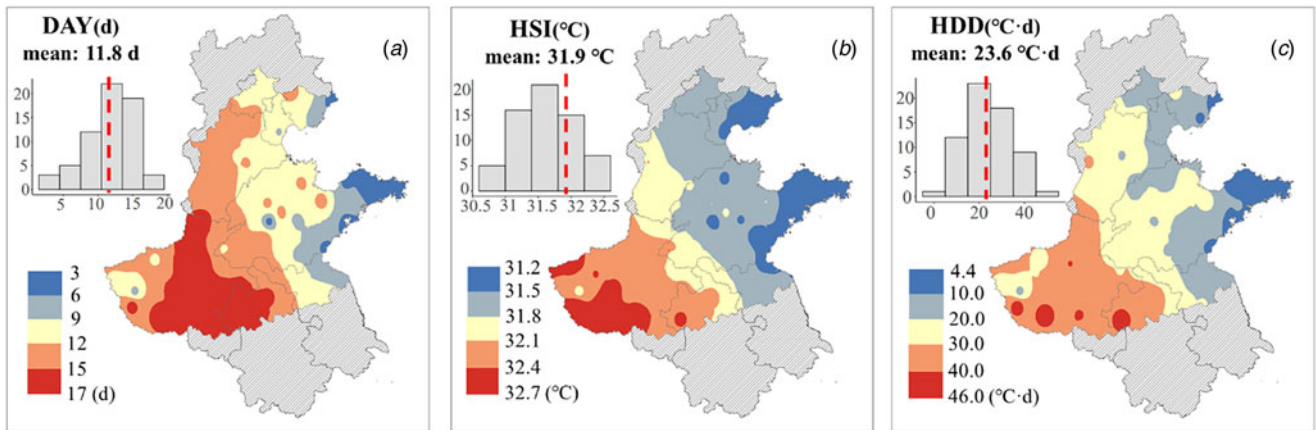
**Figure 3.** Heat stress indices during the post-silking period averaged over 1981–2019 in the Huang-Huai-Hai Plain of China. The histogram is the site distribution of DAY, HSI, HDD and the red dashed line indicates the mean value. (a) DAY, accumulated heat stress days; (b) HSI, heat stress intensity; (c) HDD, heat degree-days.

was obvious spatial consistency among these three heat stress indices, and the main hotspots of heat stress occurred in the southwest regions (parts of HN and SW sub-regions) (Fig. 3).

The average value of DAY in the HN sub-region was up to 15 days, which is 5 d more than that of SD sub-region. The average HSI in the HN sub-region was above 32.0°C, which is 0.4°C higher than SW and 0.7°C higher than the SD and JJJ sub-regions. The average HDD in HN and SW were 35.2 and 30.0°Cd, respectively, about two times than that in JJJ and SD sub-regions.

### Trends of heat stress during post-silking period

At the regional scale, DAY, HSI and HDD during the PSP increased with an average rate of 0.67 d/decade, 0.1°C/decade and 3.14°Cd/decade over the last four decades (Fig. 4). Spatially, the trend of DAY, HSI and HDD were ranged −2.7~3.1 d/decade, −0.2~0.5°C/decade and −5~15°Cd/decade, respectively. The trend of heat stress is high in southwest regions but relatively slow in the northeast regions. The heat stress in the JJJ sub-region
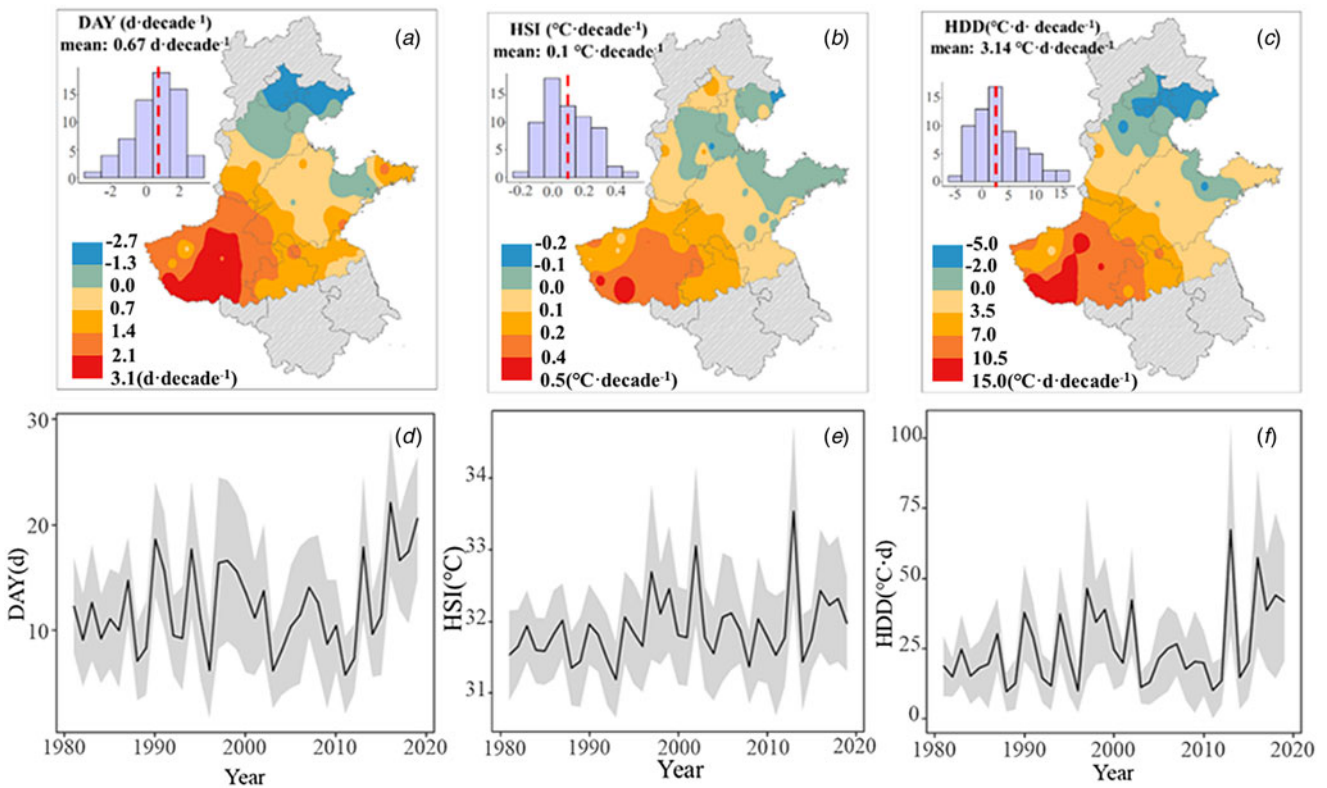


**Figure 4.** Temporal trends of heat stress indices during the post-silking period of averaged over 1981–2019 in the summer maize in the Huang-Huai-Hai Plain of China. The histogram is the site distribution of DAY, HSI, HDD and the red dashed line indicates the mean trend. (a) is the tendency rate of DAY (accumulated heat stress days); (b) is the tendency rate of heat stress intensity (HSI); (c) is the tendency rate of heat degree-days (HDD). (d), (e) and (f) is the temporal trend of DAY, HSI and HDD from 1981 to 2019; the black line is the mean value of the time series in the Huang-Huai-Hai Plain and the grey fill area refers to one standard deviation of time series.

**Table 2.** Fitting function test results of each station in The Huang-Huai-Hai Plain

| Probability function model | Number of compliant sites | Number of non-compliant sites | Number of optimal distribution sites |
|---|---|---|---|
| Normal distribution | 63 | 1 | 9 |
| Exponential distribution | 45 | 19 | 5 |
| Weibull distribution | 64 | 0 | 45 |
| Cauchy distribution | 64 | 0 | 4 |
| Poisson distribution | 7 | 57 | 0 |

**Table 3.** Classification of heat degree-days (HDD) during the post-silking period of summer maize in The Huang-Huai-Hai Plain

| Classification | HDD value |
|---|---|
| Mild heat stress | $9.4 \leqslant HDD < 19.4$ |
| Moderate heat stress | $19.4 \leqslant HDD < 34.2$ |
| Severe heat stress | $34.2 \leqslant HDD$ |

### Hazard assessment of heat stress for summer maize

The regional mean hazard probability of mild, moderate and severe heat stress were 16.6, 9.3 and 4.5%, respectively. We found that there was obvious difference for major heat stress categories for each sub-region (Fig. 6). In HN sub-region, there were similarly values of hazard probability for mild, moderate and severe heat stress, with the region average were 12.6, 10.1 and 8.6%, respectively. However, the heat stress in JJJ sub-region was mainly characterized by mild and moderate categories. The probability of mild heat stress ranged from 9.3 to 33.5% with the average of 21.6%; the maximum probability of moderate heat stress was 20.8%, and the minimum value was 3.5%; the probability of severe heat stress was less than 10%. The SW sub-region is mainly mild (16.3%) and moderate (10.9%) categories. For SD sub-region, the heat stress was mainly mild heat stress (0∼33.5%), and moderate and severe heat stress hazard probability were less than 10%.

At the regional scale, the heat stress hazard index ($M$) was 0.48 during 1981 to 2019 (Fig. 7). Spatially, the heat stress hazard index ranged from 0 to 0.77, and longitudinal gradients ($P < 0.01$) were found. Thus, the highest values were in the western regions, but relative lower values were located in the eastern regions.

During 1981–2019, areas of four levels of hazard of heat stress, low, medium, high and heavy accounted for 5.9, 31.5, 60.2 and 2.4% of the study region's area (Fig. 7c), respectively. High (with $M$ index between 0.5 and 0.75) and heavy (with index larger than 0.75) hazard was detected in HN, western SW, most JJJ and western SD sub-regions. Medium (with index between 0.25 and 0.5) hazard was mainly in central SD and eastern SW sub-regions, and low (with index no greater than 0.25) hazard was in eastern SD sub-region.

Heat stress hazard index ($M$) will increase in the future at all regions (Fig. 8), particularly after 2060. Under SSP1–2.6, $M$ were 0.34 and 0.43 in 2040s and 2080s, which similar to the values during the historical period. Under SSP3–7.0, $M$ changed from 0.63 to 0.88 in the 2020 to 2100, and 0.40 higher than historical. Under SSP5–8.5, $M$ ranged from 0.41 to 1.10, 0.95 to 1.20 during the 2040s and 2080s respectively, about two times than historical period.

showed an overall downward trend, the average trends of DAY, HSI and HDD were −1.3 d/decade, −0.1°C/decade and −5°Cd/decade. And sub-regions with the largest increase is HN, followed by SW. The trends of DAY, HSI and HDD in HN were 2.1 d/decade, 0.3°C/decade and 6.7°Cd/decade, respectively, and in SW were 1.4 d/decade, 0.2°C/decade and 6°Cd/decade. However, no significant trends were observed in SD sub-region.

### Construction of the index of classification for heat stress

According to the results of K-S test, among the 64 sites, the optimal distribution of HDD sequences in 45 (70%) sites was Weibull distribution (Table 2). Therefore, the Weibull distribution was selected as the optimal distribution function of HDD.

The cumulative probability function of the Weibull distribution for HDD was shown in Fig. 5. Then, the iCDF was used to determine the threshold of heat stress classification. iCDF (25%), iCDF (50%) and iCDF (75%) were 9.4, 19.4 and 34.2°Cd, respectively. Therefore, the index range for three classifications of heat stress during the PSP of summer maize in the HHH Plain was obtained (Table 3).
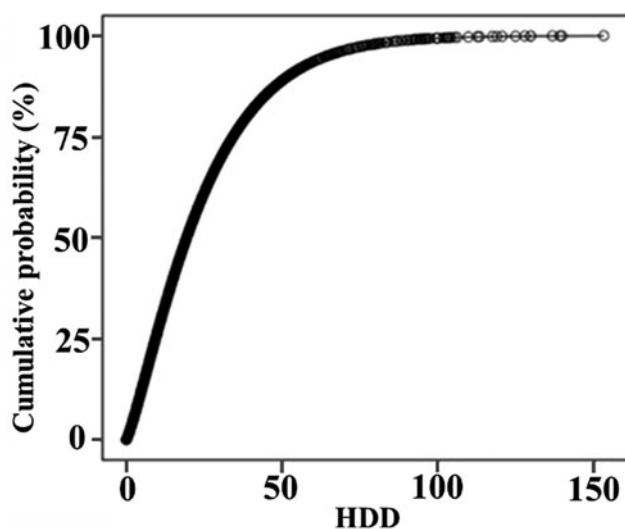
### Discussion

The impact of heat stress on crop production has received increasing attention recently (El-Sappah *et al.*, 2022; Sun *et al.*, 2023). However, insufficient attention had been paid to the change of heat stress and the occurrence risk during historical crop growth, so could not take countermeasures against heat stress in advance (Gobin, 2012; Verma *et al.*, 2020). In this study, we used the daily maximum temperature ⩾30°C as the heat stress threshold during the PSP of summer maize (Schauberger, *et al.*, 2017), and taken



**Figure 5.** The cumulative probability distribution functions of Weibull distribution of HDD (heat degree-days) during the post-silking period of summer maize.
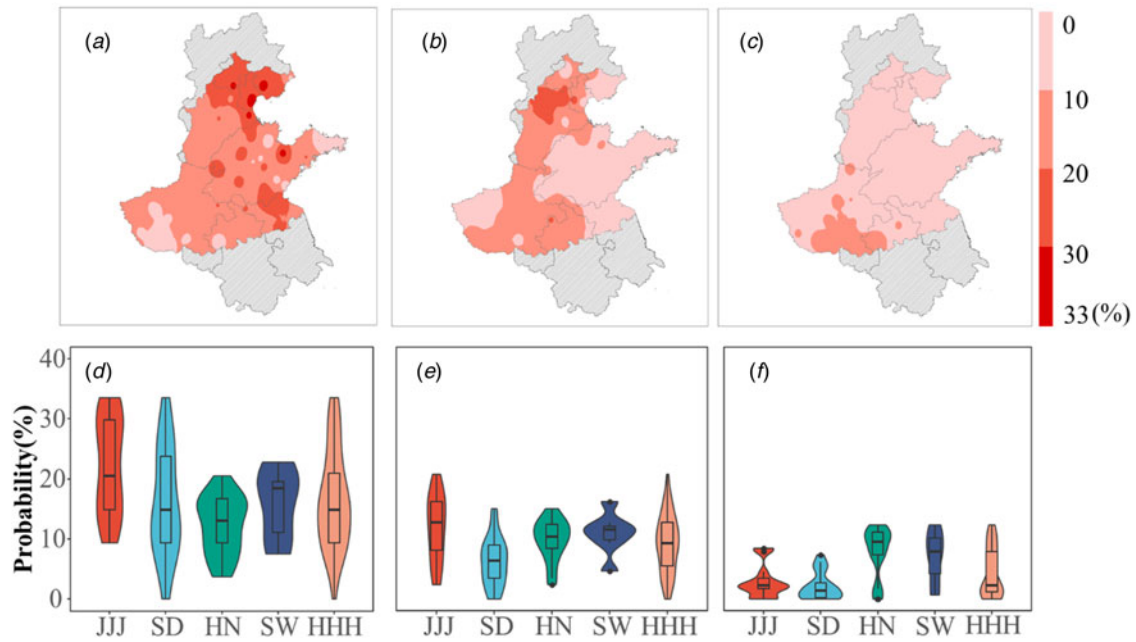
**Figure 6.** Hazard probability of different categories of heat stress during the post-silking period of summer maize in the Huang-Huai-Hai Plain of China. (a, d) Mild heat stress, (b, e) Moderate heat stress, (c, f) Severe heat stress. (JJJ, Beijing-Tianjin-Hebei region; SD, Shandong province; HN, Henan province; SW, Jiangsu and Anhui provinces; HHH, the Huang-Huai-Hai Plain).



**(c)** Hazard index class ratios for four subregions(%)

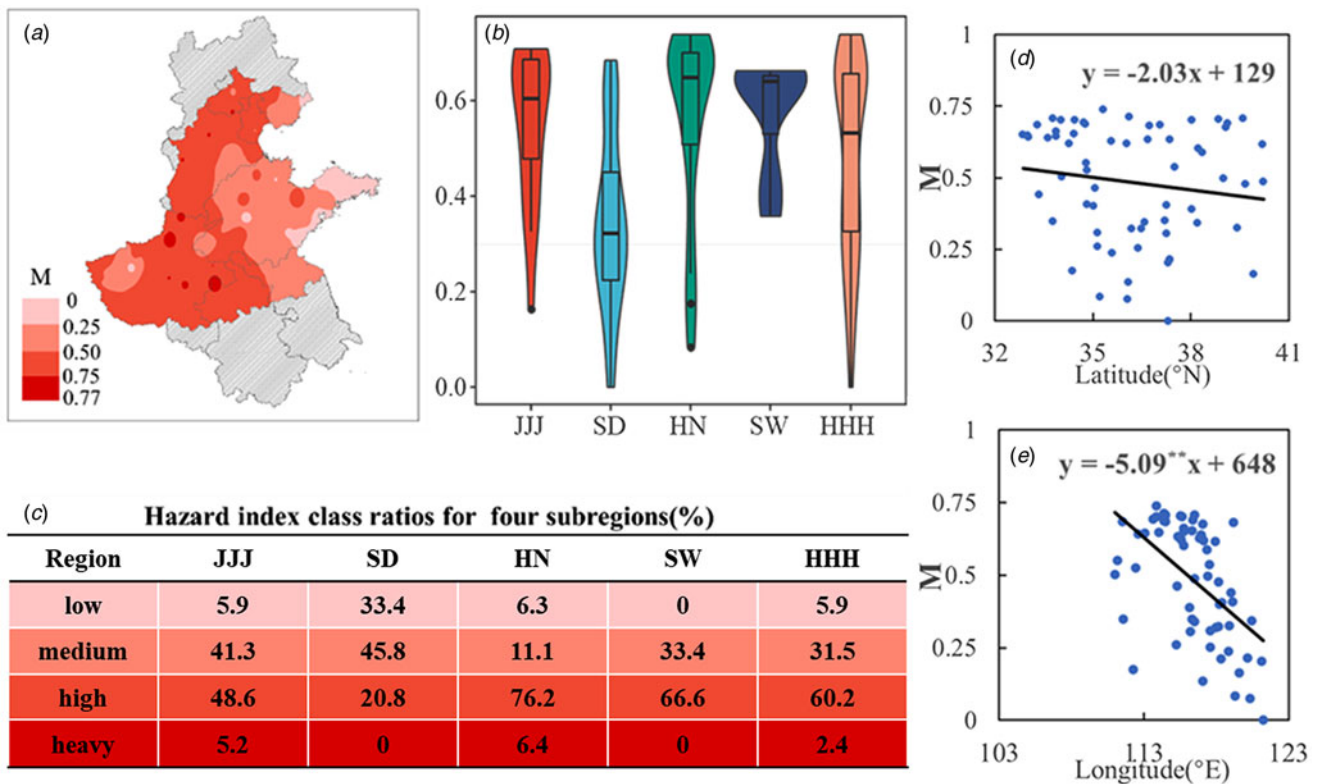| Region | JJJ | SD | HN | SW | HHH |
|---|---|---|---|---|---|
| low | 5.9 | 33.4 | 6.3 | 0 | 5.9 |
| medium | 41.3 | 45.8 | 11.1 | 33.4 | 31.5 |
| high | 48.6 | 20.8 | 76.2 | 66.6 | 60.2 |
| heavy | 5.2 | 0 | 6.4 | 0 | 2.4 |

**Figure 7.** (a, b) Hazard probability of heat stress during the post-silking period of summer maize in the Huang-Huai-Hai Plain of China. (c) Hazard index class rations for four sub-regions (heavy level with *M* index larger than 0.75; high level with *M* index between 0.5 and 0.75; medium level with *M* index between 0.25 and 0.5; low level with *M* index no greater than 0.25). (d, e) Correlations between the hazard probability of heat stress for summer maize and (d) latitude and (e) longitude during the post-silking period (JJJ, Beijing-Tianjin-Hebei region; SD, Shandong province; HN, Henan province; SW, Jiangsu and Anhui province; HHH, the Huang-Huai-Hai Plain). **, * indicate significance at $P < 0.01$, and $P < 0.05$.
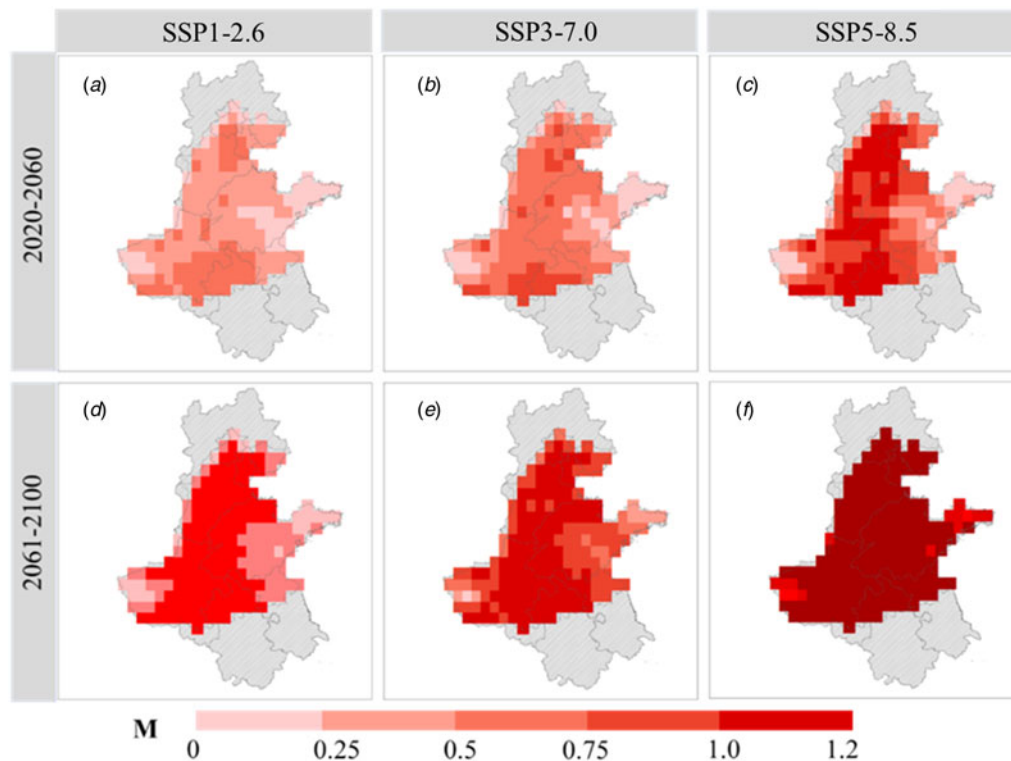
**Figure 8.** Hazard probability of heat stress during the post-silking period of summer maize in the Huang-Huai-Hai Plain of China under SSP1–2.6 (a, d), SSP3–7.0 (b, e) and SSP5–8.5 (c, f) (the average value of five GCM models: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1.2-HR, MRI-ESM2.0, UKESM1.0-LL).

DAY, HSI and HDD as the heat stress indices to explore the spatial and temporal trend of heat stress of maize. Based on HDD, the iCDF was used to construct the index of heat stress classification during the PSP, which is suitable for the summer maize planting areas in HHH Plain. Then, the hazard assessment of heat stress was carried out using information diffusion theory. Hazard assessment of heat stress can help us develop better adaptation measures to mitigate the negative impacts of climate warming on maize yield.

During the maize growing season, extreme climate events occur frequently (Zhang *et al.*, 2014; Zhang *et al.*, 2021a, 2021b), though the frequency in different maize growth regions varied. So it was important to identify the major agrometeorological events in each region. Such information is critical to the local maize community to make proactive decisions to avoid disasters. In HHH Plain, we found that heat stress occurred in most areas over the past decades, and the hazard index ranging from 0 to 0.77 (Fig. 7a). Heat stress injury is usually caused by high temperatures and long duration (Orlov *et al.*, 2020; Schwingshackl *et al.*, 2021). Therefore, due to the strong HSI and long heat stress days in Henan province, it was considered to be a high-hazard area, with a wide range of disasters, high frequency and severity, while Shandong province has the lowest hazard of heat stress. This may be related to the location of the sea and land. Hence, this indicates the importance of considering the different spatial distribution of climate impacts for agriculture (Guan *et al.*, 2021).

Information diffusion, K-S tests, Weibull distribution and iCDF were selected to compute the heat stress grade index of summer maize and carry out hazard assessment in this study. In the previous study on disaster risk assessment, computations based on information diffusion theory have elucidated relative

accuracy in risk estimation (Hao *et al.*, 2012). This method uses small sample site data for hazard assessment, avoiding errors caused by limited sample data. The iCDF reflects the variety regulation of discrete samples of maize theoretically, and avoids the effects of subjective factors (Jena *et al.*, 2014). Such methods are more valid in the analysis of limited samples and choosing other existing approaches if sufficient date available, such as copula functions, bivariables and multivariate probabilistic estimates (Zhang *et al.*, 2018a), for longer data series would benefit distribution fitting of variables. The use of the heat stress indices can serve as an effective methodology to assist in the risk of heat stress of maize (Yang *et al.*, 2020; Ye *et al.*, 2022). Generally, the establishment of heat stress grade index and M results can partially help to adapt climate change in the agricultural system of study region.

There are many ways to reduce heat stress effects during the PSP of summer maize, breeding heat tolerant hybrids is the most economical and effective method. Heat tolerant which was achieved by a number of morpho-physiological, biochemical and molecular adjustments. At cellular level, high temperatures trigger the expression of certain genes and increase the accumulation of certain metabolites which may enhance the heat enduring ability of plants and thus heat tolerance (Hasanuzzaman *et al.*, 2013). So heat tolerant maize lines were able to remain relatively high grain yield under high temperature condition (Tiwari and Yadav, 2019; Dong *et al.*, 2021). Plant hormones as efficient regulators can enhance plant stress resistance (Mitra *et al.*, 2021; Yan, 2021); increased organic fertilization can slow down plant root senescence, increased potassium fertilization can increase the water content of plant leaves, and meteorological annual forecasts with reasonable fertilization are important for maize to resist heat

stress (Li and Zheng, 1996; Li *et al.*, 1999). At the same time, rational irrigation can reduce field temperature and enhance transpiration of plants (Yin *et al.*, 2015); therefore, in field management, measures such as spraying exogenous hormones or regulating water and fertilizer can be taken to alleviate the inhibitory effect of heat stress on maize growth, so as to effectively reduce the adverse effects of heat stress. In addition, it is also necessary to strengthen the forecast and early warning of high temperature weather, improve the level of meteorological services for agriculture and guide farmers to take preventive measures in a timely manner. But, in fact, the heat stress grade of summer maize during the PSP is affected by the biological characteristics of the plant itself and environment, such as variety stress resistance, genotype cultivation measures and soil environment, and may vary in different regions (Wei *et al.*, 2021; Zhang *et al.*, 2021a, 2021b). With the variety replacement and climate change, it is necessary to further explore the heat stress threshold for the local hybrids.

## Conclusions

The threshold of classification for mild, moderate and severe heat stress were 9.4, 19.4 and 34.2°Cd, respectively. At the regional scale, heat stress hazard index ($M$) was 0.48, ranged from 0 to 0.77 during 1981 to 2019. The highest values were in the western regions, but relative lower values were located in the eastern regions. In the future climate change scenarios, $M$ will be increased. Under SSP5–8.5, $M$ ranged from 0.95 to 1.20 during the 2080s, about two times than historical period.

## References

**China Meteorological Administration** (2008) GB/T 21985-2008: Temperature index of high temperature harm for main crops.
**CIMMYT** (2011) MAIZE – global alliance for improving food security and the livelihoods of the resource-poor in the developing world, edited. CYMMIT, Proposal submitted by CIMMYT and IITA to the CGIAR Consortium Board.
**Corey L, Pedram R and Navin R** (2016) Influence of extreme weather disasters on global crop production. *Nature* **529**, 84–87.
**Couëdel A, Edreira JIR, Lollato RP, Archontoulis S, Sadras V and Grassini P** (2021) Assessing environment types for maize, soybean, and wheat in the United States as determined by spatio-temporal variation in drought and heat stress. *Agricultural and Forest Meteorology* **307**, 108513.
**Cucchi M, Weedon GP, Amici A, Bellouin N and Buontempo C** (2020) WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. *Earth System Science Data* **12**, 2097–2120.
**Dong X, Guan L, Zhang PH, Liu XL, Li SJ, Fu ZJ, Tang L, Qi ZY, Qiu ZG, Jin C, Huang SB and Yang H** (2021) Responses of maize with different growth periods to heat stress around flowering and early grain filling. *Agricultural and Forest Meteorology* **303**, 108378.

**El-Sappah AH, Rather SA, Wani SH, Elrys AS, Bilal M, Huang QL, Dar ZA, Elashtokhy MA, Soaud N, Koul M, Mir RR, Yan K, Li J, El-Tarabily KA and Abbas M** (2022) Heat stress-mediated constraints in maize (*Zea mays*) production: challenges and solutions. *Frontiers in Plant Science* **13**, 1187.
**FAO** (2016) FAOSTAT.FAO. Available at http://faostat.fao.org/site/567/default.aspx#ancor (accessed 16.09.18).
**Gao R, Guo ZX, Chen SY and Han T** (2009) Change characteristic of summer air temperature in east monsoon area in China over recent 46 years. *Scientia Geographica Sinica* **29**, 255–261.
**Gao Z, Feng HY, Liang XG, Lin S, Zhao X, Shen S, Du X, Cui YH and Zhou SL** (2021) Adjusting the sowing date of spring maize did not mitigate against heat stress in the North China Plain. *Agricultural and Forest Meteorology* **298**, 108274.
**Gobin A** (2012) Impact of heat and drought stress on arable crop production in Belgium. *Natural Hazards and Earth Systems Sciences* **12**, 1911–1922.
**Guan Y, Liu JH, He QJ, Li RC, Mi XY and Qin ZH** (2021) Risk probability of heat injury during summer maize flowering period in North China Plain based on information diffusion theory. *Chinese Journal of Agrometeorology* **42**, 606–615.
**Hao L, Zhang XY and Liu SD** (2012) Risk assessment to China's agricultural drought disaster in county unit. *Natural Hazards* **61**, 785–801.
**Hasanuzzaman M, Nahar K, Alam MM, Roychowdhury R and Fujita M** (2013) Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *International Journal of Molecular Sciences* **14**, 9643–9684.
**Huang CF** (2005) *Risk Assessment of Natural Disaster*. Beijing: Science Press.
**Huo ZG and Jiang Y** (2006) Risk analysis of water demand and supply of winter wheat in North China based on irrigation. *Transactions of the Chinese Society of Agricultural Engineering* **22**, 79–84.
**Huo ZG, Zhang HY, Li CH, Kong R and Jiang MY** (2023) Review on high temperature heat damage on maize in China. *Journal of Applied Meteorological Science* **34**, 1–14.
**IPCC** (2021) *Climate Change 2021: The Physical Science Basis*. Cambridge: Cambridge University Press.
**IPCC** (2023) *AR6 Synthesis Report: Climate Change 2023*. Cambridge: Cambridge University Press.
**Jena PP, Chatterjee C, Pradhan G and Mishra A** (2014) Are recent frequent high floods in Mahanadi basin in eastern India due to increase in extreme rainfalls? *Journal of Hydrology* **517**, 847–886.
**Jiang MN, Liu CS and Gao W** (2018) Analysis of spatial and temporal variation in potential summer maize yield and its response to climate change in the North China Plain. *Chinese Journal of Eco-Agriculture* **26**, 865–876.
**Lange S, Menz C, Gleixner S, Müller SH and ISIMIP cross-sectoral science team** (2021) WFDE5 over land merged with ERA5 over the ocean (W5E5 v2.0). https://doi.org/10.48364/ISIMIP.342217.
**Li MD and Zheng SX** (1996) The impacts of potassium nutrition on maize development and drought resistance. *Soils and Fertilizers* **10**, 10–12.
**Li FX, Wang JL, Li YL and Diao XQ** (1999) The impacts of zinc on summer maize development and yield. *Journal of Maize Science* **7**, 72–76.
**Liu JB** (2012) *Maize Cultivation in North China*. Beijing: China Agricultural Science and Technology Press.
**Liu ZJ, Hubbard KG, Lin XM and Yang XG** (2013) Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. *Global Change Biology* **19**, 3481–3492.
**Liu C** (2018) Study On the rule of high temperature heat damage of summer maize in Zhengzhou by using the temperature three range theory under the background of global climate change. *Modern Agriculture Research* **9**, 20–22.
**Liu YQ, You M, Zhu JL, Wang F and Ran RP** (2019) Integrated risk assessment for agricultural drought and flood disasters based on entropy information diffusion theory in the middle and lower reaches of the Yangtze River, China. *International Journal of Disaster Risk Reduction* **38**, 101194.
**Lizaso JI, Ruiz-Ramos M, Rodríguez L, Gabaldon-Leal C, Oliveira JA, Lorite IJ, Sánchez D, García E and Rodríguez A** (2018) Impact of high temperatures in maize: phenology and yield components. *Field Crops Research* **216**, 129–140.
**Lobell DB, Schlenker W and Costa-Roberts J** (2011) Climate trends and global crop production since 1980. *Science (New York, N.Y.)* **333**, 616–620.

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

Lu WT, Yu H, Cao SN and Chen CQ (2015) Effects of climate warming on growth process and yield of summer maize in Huang-Huai-Hai Plain in last 20 years. *Scientia Agricultura Sinica* 48, 3132–3145.

Mayer LI, Edreira JIR and Maddonni GA (2014) Oil yield components of maize crops exposed to heat stress during early and late grain-filling stages. *Crop Science* 54, 2236–2250.

Mitra A, Kataki S, Singh AN, Gaur A, Razafindrabe BHN, Kumar P, Chatterjee S and Gupta DK (2021) Plant stress, acclimation, and adaptation: a review. *Plant Growth and Stress Physiology*, 1–22.

Orlov A, Sillmann J, Aunan K, Kjellstrom T and Aaheim A (2020) Economic costs of heat-induced reductions in worker productivity due to global warming. *Global Environmental Change* 63, 102087.

Rohde MM (2023) Floods and droughts are intensifying globally. *Nature Water* 1, 226–227.

Schauberger B, Archontoulis S, Arneth A, Balkovic J, Ciais P, Deryng D, Elliott J, Folberth C, Khabarov N, Müller C, Pugh TAM, Rolinski S, Schaphoff S, Schmid E, Wang XH, Schlenker W and Frieler K (2017) Consistent negative response of US crops to high temperatures in observations and crop models. *Nature Communications* 8, 13931.

Schmitt J, Offermann F, Söder M, Frühauf C and Finger R (2022) Extreme weather events cause significant crop yield losses at the farm level in German agriculture. *Food Policy* 112, 102359.

Schwingshackl C, Sillmann J, Vicedo-Cabrera AM, Sandstad M and Aunan K (2021) Heat stress indicators in CMIP6: estimating future trends and exceedances of impact-relevant thresholds. *Earth's Future* 9, e2020EF001885.

Shimono (2011) Earlier rice phenology as a result of climate change can increase the risk of cold damage during reproductive growth in northern Japan. *Agriculture, Ecosystems & Environment* 144, 201–207.

Sun J, Wang HQ, Ren H, Zhao B, Zhang JW, Ren BZ and Liu P (2023) Maize (*Zea mays* L.) responses to heat stress: mechanisms that disrupt the development and hormone balance of tassels and pollen. *Journal of Agronomy and Crop Science* 00, 1–15.

Tao F, Zhang LL, Zhang Z and Chen Y (2022) Climate warming outweighed agricultural managements in affecting wheat phenology across China during 1981–2018. *Agricultural and Forest Meteorology* 316, 108865.

Tian HW (2016) Study on agricultural climate resources in Huang-Huai-Hai area during summer maize growing season. *Meteorological and Environmental Sciences* 39, 56–61.

Tiwari YK and Yadav SK (2019) High temperature stress tolerance in maize (*Zea mays* L.): physiological and molecular mechanisms. *Journal of Plant Biology* 62, 93–102.

Verma S, Kumar N, Verma A, Singh H, Siddique KH and Singh NP (2020) Novel approaches to mitigate heat stress impacts on crop growth and development. *Plant Physiology Reports* 25, 627–644.

Wang P, Zhang Z, Song X, Chen Y, Wei X, Shi PJ and Tao FL (2014) Temperature variations and rice yields in China: historical contributions and future trends. *Climatic Change* 124, 777–789.

Wang LJ, Liao SH, Huang SB, Ming B and Meng QF (2018) Increasing concurrent drought and heat during the summer maize season in Huang-Huai-Hai Plain, China. *International Journal of Climatology* 38, 3177–3190.

Wang YY, Sheng DC, Zhang P, Dong X, Yan Y, Hou XF, Wang P and Huang SB (2021) High temperature sensitivity of kernel formation in different short periods around silking in maize. *Environmental and Experimental Botany* 183, 104343.

Wei D, Zeng XH, Luo N, Wang LJ, Meng QF and Wang P (2021) Effect of extreme high temperature on summer maize yield in Beijing-Tianjin-Hebei region. *Journal of China Agricultural University* 26, 1–17.

Wu JZ, Zhang J, Ge ZM, Xing LW, Han SQ, Chen S and Kong FT (2021) Impact of climate change on maize yield in China from 1979 to 2016. *Journal of Integrative Agriculture* 20, 289–299.

Xue CY, Ma ZH and Hu CD (2016) Spatiotemporal characteristics of drought during summer maize rowing season in Huang-Huai-Hai area for recent 40 years. *Journal of Natural Disasters* 25, 1–14.

Yan YN (2021) *Effects of Spraying Exogenous Hormones at Silking Ston the Grain Yield and Quality Under Post-Silking Heat Stress for Waxy Maize.* Yangzhou: Yangzhou University.

Yang H, Shen X, Lu DL and Lu WP (2017) Effects of heat stress durations at grain formation stage on grain yield and starch quality of waxy maize. *Scientia Agricultura Sinica* 50, 2071–2082.

Yang JY, Huo ZG, Li XX, Wang PJ and Wu DR (2020) Hot weather event-based characteristics of double-early rice heat risk: a study of Jiangxi province, South China. *Ecological Indicators* 113, 106148.

Yang JY, Huo ZG, Wang PJ, Wu DR, Mao HD and Kong R (2021) Evaluation index construction and hazard risk assessment on apple drought in Northern China. *Journal of Applied Meteorological Science* 32, 25–37.

Ye P, Liu KQ, Shen SH, Liu KW, Liu ZX and Deng YJ (2022) Risk analysis and regionalization of heat damage during heading and flowering stage of mid-season rice in Hubei Province. *Chinese Agricultural Science Bulletin* 38, 110–117.

Yin XG, Wang M, Kong QX, Wang ZB, Zhang HL, Chu QQ, Wen XY and Chen F (2015) Impacts of high temperature on maize production and adaptation measures in Northeast China. *Chinese Journal of Applied Ecology* 26, 186–198.

Yu Y, Jiang ZH, Wang GJ, Kattel GR, Chuai XW, Shang Y, Zou YF and Miao LJ (2022) Disintegrating the impact of climate change on maize yield from human management practices in China. *Agricultural and Forest Meteorology* 327, 109235.

Zhang Z, Chen Y, Wang P, Zhang S, Tao FL and Liu XF (2014) Spatial and temporal changes of agro-meteorological disasters affecting maize production in China since 1990. *Natural Hazards* 71, 2087–2100.

Zhang P, Chen GY, Geng P, Gao Y, Zheng L, Zhang SS and Wang P (2017) Effects of high temperature during grain filling period on superior and inferior kernel's development of different heat sensitive maize varieties. *Scientia Agricultura Sinica* 50, 2061–2070.

Zhang L, Yang BY, Guo AH, Huang DP and Huo ZG (2018a) Multivariate probabilistic estimates of heat stress for rice across China. *Stochastic Environmental Research and Risk Assessment* 32, 3137–3150.

Zhang LL, Zhang Z, Chen Y, Wei X and Song X (2018b) Exposure, vulnerability, and adaptation of major maize-growing areas to extreme temperature. *Natural Hazards* 91, 1257–1272.

Zhang Q, Han JH and Yang XY (2021a) Effects of direct heat stress on summer maize and risk assessment. *Theoretical and Applied Climatology* 146, 755–765.

Zhang Q, Han JH and Yang ZQ (2021b) Hazard assessment of extreme heat during summer maize growing season in Haihe Plain, China. *International Journal of Climatology* 41, 4794–4803.

Zhang JX, Ge JZ, Ma W, Ding ZS, Wang XB, Li CF, Zhou BY and Zhao M (2022) Research advance on annual water use efficiency of winter wheat-summer maize cropping system in North China Plain. *Acta Agronomica Sinica* 49, 879–892.

Zhao C, Liu B, Piao SL, Lobell DB, Huang Y, Huang MT, Yao YT, Bassu S, Ciais P, Durang J-S, Elliott J, Ewert F, Janssens IA, Li T, Lin RD, Liu Q, Martre P, Müller C, Peng SS, Peñuelas J, Ruane AC, Wallach D, Wang T, Wu DH, Liu Z, Zhu Y, Zhu ZC and Asseng S (2017) Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences* 114, 9326–9331.

Zheng SR, Hu Q, He HY, Xing MY, Gao HR, Liu YY, Ma XQ and Pan XB (2022) Temporal and spatial variation characteristics of radiation in winter-summer maize growing season in the North China Plain during 1961–2020. *Journal of China Agricultural University* 27, 26–37.

Zhou BY, Sun XF, Wang D, Ding ZS, Li CF, Ma W and Zhao M (2019) Integrated agronomic practice increases maize grain yield and nitrogen use efficiency under various soil fertility conditions. *The Crop Journal* 7, 527–538.