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Effect of High-Temperature Events When Heading into the Maturity Period on Summer Maize (*Zea mays* L.) Yield in the Huang-Huai-Hai Region, China

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Abstract: The predicted increase in the frequency of extreme climatic events in the future may have a negative effect on cereal production, but our understanding of the historical trends of high-temperature events associated with climate change and their long-term impact on summer maize yield is limited. Based on an analysis of historical climate and summer maize yield data from 1980 to 2016 in the Huang-Huai-Hai (3H) region of China, we calculated two high-temperature event indices, namely, high-temperature hours (HTH) and high-temperature degrees (HTD, the sum of the differences between 35 °C and above), and then investigated the temporal trend of high-temperature events from maize heading to maturity and their impact on the yield of summer maize. Our results indicated that the air temperature showed a significant upward trend when heading into the maturity period of summer maize in the 3H region from 1980–2016 and that the increase was greater in the northern Huang-Huai-Hai (N3H) region than in the southern Huang-Huai-Hai (S3H) region. The intensity of high-temperature events when heading into the maturity period increased considerably from 1980 to 2016 in the 3H region, especially in the S3H region. The HTH and HTD increased by 1.30 h and 0.80 °C per decade in the S3H region, respectively. Moreover, a sensitivity analysis of panel data showed that the increases in HTH and HTD when heading into the maturity period had a consistent negative effect on yield in S3H and N3H regions; this effect was more obvious in the S3H region. In the S3H region, a 1 h increase in HTH was found to be associated with a 0.45–1.13% decrease in yield and a 1 °C increase in HTD could result in a yield loss of 1.34–4.29%. High-temperature events were detrimental to summer maize production, and the severity of this effect was projected to increase in the 3H region. In this study, we used two indices (HTH and HTD) to quantify the impact of high-temperature events on summer maize yield during the critical growth phase (heading to maturity) at a small timescale (hours and days). The results of this study can provide a reference for policymakers to use in the formulation of corresponding climate change adaptation strategies.

Keywords: climate change; high-temperature events; summer maize; heading; maturity; yield

1. Introduction

With global climate warming, the frequency and severity of extreme weather events have increased [1,2], which have had a negative impact on the growth and development of crops [3,4]. High temperatures that exceed critical thresholds for plants are usually referred to as heat stress, and crops are more sensitive to high temperatures during their reproductive stages than during their vegetative stages [5]. During this critical growth period, even short-term high-temperature stress can cause drastic reductions in yield [6–9]. For example, high-temperature stress inhibited the elongation of

rice pollen tubes during the anthesis stage, which resulted in poor fertilization and ultimately spikelet sterility [10,11]. Similarly, high-temperature stress during the flowering or grain filling stages of wheat reduced the photosynthetic rate, increased the damage to the thylakoid membrane, and decreased yield by 29% and 44%, respectively [9]. Furthermore, Barkley et al. [12] indicated that wheat grain yield was reduced by 21% per 1 °C increase during the reproductive stage. Therefore, understanding the response of crops to high temperatures during critical periods is essential to ensure cereal production.

Maize is among the three most important grain crops in the world and provides a stable source of food for many populations [13]. With global population growth, the demand for maize as food, feed, and fuel continues to rise and is projected to reach a new peak by 2024 [14]. Numerous studies have been conducted to explore the responses of maize to increased temperatures [15–17]. High temperatures accelerate the development of maize, shorten its growth period, and reduce photosynthetic product accumulation [18,19]. Gabaldón-Leal et al. [20] found that the critical maximum temperature at flowering ranged from 32–35 °C for maize and, at temperatures above 35 °C, the reproductive organs develop poorly, pollination and fertilization cannot proceed normally, and grain filling and the seed-setting rate decrease, which ultimately leads to reduced production [21–24]. High-temperature stress has become a major threat to current and future maize production in some regions [19].

China is the second largest maize producer and consumer in the world [25], and the 3H region is one of the two major maize production areas in China. Changes in maize production in this region have an important influence on national food security. However, extreme weather events during the summer maize growing season in the Huang-Huai-Hai (3H) region have increased over the past decades [26,27]. High temperatures above 35 °C often occur in July and August, which is the period of tasseling and pollen dispersal, and these processes are very sensitive to high temperatures. Therefore, it is particularly important to understand the impact of the occurrence of high-temperature events at this critical stage on maize yield. However, previous studies have focused predominantly on the mechanism of the effects of high temperatures on maize yield [22,28,29] and the effect of climate change on maize growth and development [13,15,30], while few have quantified the occurrence characteristics of high-temperature events in critical stages at a smaller timescale or assessed the impact of high-temperature events on summer maize yield when heading into the maturity period in this region.

The goals of this study are (1) to evaluate the temporal trend of high-temperature events when heading into the maturity period of summer maize by calculating the daily maximum temperatures from 1980–2016 in the 3H region and (2) to quantify the effect of high-temperature events when heading into maturity on maize yield at hourly and daily timescales.

2. Materials and Methods

2.1. Study Region

The study region is located in eastern China (31°23′–42°36′ N, 110°21′–122°42′ E) and covers most of the 3H region of China (Figure 1). The study area comprises a total area of 6.6×10^5 km², and the maize-growing area in the study area accounts for 35% of the national total planting area and provides 40% of the maize production nationwide. The study area is located in the mid-latitude zone of the monsoon climatic region in eastern China. In summer (June–August), the long-term mean temperature is 24.6 °C and the precipitation is 122.9 mm, and in winter (December–February), the average temperature is −2.3 °C and the precipitation is 9.8 mm. The average annual temperature and precipitation decrease with increasing latitude from south to north. Previous research suggests that climatic factors, such as temperature, sunshine duration, and precipitation are the primary ecological factors that affect the growth and development of maize. Crop adaptability varies under different ecological conditions, and maize adapts to ecological environmental changes by adjusting its growth duration [25]. In this study, we divided the study area into two sub-regions, the southern and northern sub-regions (Figure 1). The southern region borders the subtropical zone, while the northern region borders the mid-temperate zone. There are certain differences in climatic conditions and summer

maize growth duration between the two sub-regions (Table 1). In addition, we also provide the air temperatures and average phenological dates of the summer maize growing season in the 3H region over the past 37 years (Table 2).

Figure 1. The location of the study area in China and the distribution of the meteorological stations. S3H and N3H indicate the southern Huang-Huai-Hai region and the northern Huang-Huai-Hai region, respectively.

Table 1. The annual average values of climate factors and the average phenological dates of summer maize in the Huang-Huai-Hai region from 1980 to 2016.

Region	T (°C)	SSD (h)	Prec (mm)	Sowing	Heading	Maturity	VGP (d)	RGP (d)	WGP (d)
S3H	14.29	2129	771.4	6/11	8/4	9/18	54	45	99
N3H	10.44	2480	491.6	6/16	8/9	9/26	54	48	102

Annual average temperature (T); sunshine duration (SSD); precipitation (Prec); vegetative growth period (VGP); reproductive growth period (RGP); whole growth period (WGP).

2.2. Data Sources

The data, which mainly include meteorology, phenology, and yield data, were obtained from three databases. A comprehensive analysis of these data was conducted to characterize the occurrence of high-temperature events when heading into the maturity period of summer maize and its relationship with yield in the study area. The first data set came from the National Meteorological Information Center of the Central China Meteorological Administration (<http://data.cma.cn/>) and contained daily maximum temperature (T_{max}), average temperature (T_{avg}), minimum temperature (T_{min}), and precipitation data. In the study area, 112 meteorological stations with complete records were selected and the high-temperature event indices (high-temperature hours (HTH) and high-temperature degrees (HTD)) were calculated by using the daily T_{max} data observed when heading to maturity in summer maize during 1980–2016. These first databases included 60 and 52 stations in the S3H and N3H regions, respectively. The spatial positional data for each meteorological station were obtained from the National Geomatics Center of China (Figure 1).

The second data set consists of the phenological data (sowing, heading, and maturity dates) for summer maize from 1980–2016. In the study, we defined the vegetative growth period as that from sowing to heading and the reproductive growth period as that from heading to maturity. These data also collected from the National Meteorological Administration to evaluate the mean values of the summer maize heading and maturity dates at each station from 1980–2016, which were regularly recorded phenological dates at these stations.

Table 2. The climatic factors and their trends during the summer maize growth season in the Huang-Huai-Hai region from 1980 to 2016.

Region	Month	T_{min}		T_{avg}		T_{max}		SSD		Prec	
		Mean (°C)	Trend (°C a ⁻¹)	Mean (°C)	Trend (°C a ⁻¹)	Mean (°C)	Trend (°C a ⁻¹)	Mean (h)	Trend (h a ⁻¹)	Mean (mm)	Trend (mm a ⁻¹)
S3H	6	19.95 ± 0.74	0.0432 **	24.61 ± 0.77	0.0303 **	29.90 ± 0.95	0.0225	198.0 ± 23.02	−0.8965 **	99.83 ± 43.07	−0.1966
	7	23.28 ± 0.89	0.0378 **	26.84 ± 0.91	0.0300 *	31.15 ± 1.04	0.0255	182.9 ± 28.23	−0.8367	189.4 ± 48.51	0.6470
	8	22.45 ± 0.86	0.0383 **	25.93 ± 0.84	0.0250	30.27 ± 0.95	0.0160	190.4 ± 33.66	−1.221 *	145.9 ± 45.75	0.7821
	9	17.42 ± 0.95	0.0508 **	21.54 ± 0.85	0.0298 *	26.62 ± 1.06	0.0124	177.7 ± 31.58	−1.184 *	75.11 ± 39.96	0.5134
N3H	6	16.57 ± 0.70	0.0361 **	22.72 ± 0.75	0.0221 *	29.20 ± 0.95	0.0195	235.6 ± 23.89	−1.283 **	67.70 ± 16.83	0.0450
	7	19.53 ± 0.84	0.0405 **	24.50 ± 0.82	0.0293 *	30.15 ± 0.99	0.0275	217.5 ± 24.27	−1.309 **	128.9 ± 39.96	0.2204
	8	18.16 ± 0.71	0.0342 **	22.93 ± 0.75	0.0311 **	28.65 ± 1.01	0.0321*	214.9 ± 24.88	−0.7685 *	105.7 ± 31.39	−0.7270
	9	12.47 ± 1.10	0.0589 **	17.80 ± 0.92	0.0332 *	24.29 ± 1.10	0.0159	202.7 ± 27.33	−1.580 **	61.25 ± 21.37	0.6554 *

Note: T_{min} , T_{avg} , T_{max} , SSD, and Prec indicate the minimum temperature, average temperature, maximum temperature, sunshine duration, and precipitation, respectively. °C a⁻¹ means 1 °C per year and h a⁻¹ means 1 h per year. *, **: significant at $p < 0.05$ and $p < 0.01$, respectively.

The third database contained the planting area, yield, and annual yield of summer maize in each province from 1980–2016, and these data were extracted from the Agricultural Information Network of China. According to the ratio of the yield to the planted area of each province, we calculated the average yield for the S3H and N3H regions to estimate the impact of high-temperature events from heading to maturity on grain yield.

2.3. Data Analysis

2.3.1. High-Temperature Event Indices

We treated 35 °C as the critical threshold of high-temperature stress to evaluate the impact of this stress on summer maize yield. The HTH and HTD were used as the main indices to describe the high-temperature events and then to analyze the occurrence and impact of high-temperature events from heading to maturity. Based on the high-temperature event indices at each station over the past 37 years, the temporal trends of the high-temperature index of the S3H, N3H, and 3H regions were fitted by simple linear regression to reveal the local and 3H-regionwide changes in recent decades. The HTH calculation method refers to Bristow and Abrecht [31], and the HTD calculation method was based on Shi et al. [32]. The calculation methods for HTH and HTD are as follows:

$$T_1 = \frac{D}{\pi} \times \arcsin \frac{(T_c - T_{\min})}{T_{\max} - T_{\min}} \quad (1)$$

$$T_2 = D - T_1 \quad (2)$$

$$HH_i = T_2 - T_1 \quad (3)$$

$$HTH = \sum_{d_h}^{d_m} HH_i \quad (4)$$

$$HTD = \sum_{d_h}^{d_m} HD_i \quad (5)$$

$$HD_i = 0, T_{\max} < T_c \quad (6)$$

$$HD_i = T_{\max} - T_c, T_{\max} \geq T_c \quad (7)$$

where T_1 and T_2 (h) are intermediate variables; D is day length (h); T_c is the critical temperature (35 °C); $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperature on day i ; HH_i is high-temperature hours above the temperature threshold of 35 °C on day i ; d_h and d_m are heading and maturity dates, respectively; HTH indicates the accumulated HH_i from heading to maturity; HD_i is the high temperature degrees on day i , and HTD indicates the accumulated HD_i from heading to maturity.

2.3.2. The Impact of High-Temperature Events on Summer Maize Yield

The yield of maize is affected by climatic factors, as well as non-climatic factors, such as variety improvement, fertilization, and cultivation practices. To analyze the relationship between climatic factors and yield more accurately, the influence of non-climatic factors must be eliminated [33]. Schlenker and Lobell [34] proposed that the linear and quadratic trends of the years can be considered to exclude the contribution of non-climatic factors to yield. Therefore, in this study, the nonlinear model of Lobell et al. [35] was used to perform a sensitivity analysis of the crop yield time series in detail from 1980 to 2016. A regional panel data analysis tool (Eviews6.0) was used to evaluate the effect of high-temperature events on summer maize yield. The specific model is as follows:

$$\log(\text{Yield}(i,t)) = ci + d_{1i} \times \text{year} + d_{2i} \times \text{year}^2 + \beta \times X(i,t) + \varepsilon(i,t) \quad (8)$$

where i is the sub-region (southern 3H (S3H) and northern 3H (N3H) region) of the study; $t = 1980, \dots, 2016$; c is a fixed effect; d is the time trend coefficient; β is the independent variable parameter; $X(i,t)$ are

independent variable parameters, including climatic factors, such as the average temperature (T_{avg}), minimum temperature (T_{min}), maximum temperature (T_{max}), and precipitation; and $\varepsilon(i,t)$ is the error term. Statistical analyses were performed using SPSS software (SPSS 25.0, SPSS, Inc., Chicago, IL, USA). Graphics were created with Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

3. Results

3.1. Variation Trends of Temperature, Precipitation, and Yield from Heading to Maturity

The changes in T_{avg} , T_{max} , and T_{min} from heading to maturity in summer maize showed an upward trend in the 3H region during 1980–2016 (Table 3). For the S3H and N3H regions during the study period, T_{avg} exhibited a significant increase and T_{min} had an extremely significant increase, but T_{max} only exhibited a significant increase in the N3H region only. Overall, the temperature increase was higher in the N3H region than in the S3H region, and the trend was that T_{min} increased most dramatically, followed by T_{avg} and T_{max} . There was no significant change in precipitation over the study period; the precipitation increased slightly, by 1.61 mm per 10-yr period, but fluctuated greatly interannually. According to the statistics, the average yield of summer maize in the 3H region was 3335 kg ha⁻¹ in the 1980s and rose to 5648 kg ha⁻¹ in 2016, with an average annual increase of approximately 64.26 kg ha⁻¹. From 1980 to 2016, yields increased significantly in the 3H region, but the difference in yield between the S3H and N3H regions was not significant. The S3H region had the highest maize grain yield at 4951 kg ha⁻¹, which was 9.55% higher than the yield of the N3H region (4519 kg ha⁻¹), but its coefficient of variation was also higher than that of the N3H region.

3.2. Variation Trends of HTH and HTD during the Heading to Maturity Period

The values of HTH and HTD from heading to maturity across the 3H region suggested an increasing trend, particularly in the S3H region, during 1980–2016 (Figure 2). The HTH values increased markedly, by 1.30 h, 0.79 h, and 1.17 h per decade in the S3H, N3H, and 3H regions, respectively. During the study period, the average values of HTH were 3.94 h and 2.68 h for the S3H and N3H regions, respectively. The increases in HTD per 10-yr period were 0.80 °C, 0.41 °C, and 0.59 °C for the S3H, N3H, and 3H regions, respectively. The average HTDs between heading and maturity during the period of 1980–2016 were 2.55 °C and 1.72 °C for the S3H and N3H regions, respectively.

Figure 2. The trends of two high-temperature index variables ((A–C), high-temperature hours (HTH); (D–F), high-temperature degrees (HTD)) between heading and maturity in the Huang-Huai-Hai summer maize region during 1980–2016. (A,D), (B,E), and (C,F) indicate the southern Huang-Huai-Hai region (S3H), northern Huang-Huai-Hai region (N3H), and whole Huang-Huai-Hai region (3H), respectively.

Table 3. Change trends in temperature, precipitation from heading to maturity and yield changes in the Huang-Huai-Hai summer maize region during 1980–2016.

Region	T_{min}		T_{avg}		T_{max}		Prec		Yield		CV
	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend	Mean	Trend	
	(°C)	(°C 10a ^{−1})	(°C)	(°C 10a ^{−1})	(°C)	(°C 10a ^{−1})	(mm)	(mm 10a ^{−1})	(kg ha ^{−1})	(kg ha ^{−1} a ^{−1})	
S3H	20.37 ± 0.70	0.360 **	24.12 ± 0.68	0.236 *	28.79 ± 0.86	0.153	184.4 ± 54.66	4.410	4951	62.02 **	16.77
N3H	16.10 ± 0.72	0.441 **	21.14 ± 0.66	0.319 **	27.20 ± 0.83	0.273 *	161.1 ± 35.97	−0.146	4519	66.37 **	14.92
3H	18.33 ± 0.69	0.400 **	22.70 ± 0.64	0.277 *	28.03 ± 0.79	0.211	173.3 ± 40.97	1.161	4780	64.26 **	15.53

Note: *, **: significant at $p < 0.05$ and $p < 0.01$, respectively.

3.3. Impacts of HTH and HTD Changes on Summer Maize Yield from Heading to Maturity

Panel data analysis was performed to identify the impacts of HTH and HTD variations on yield (Figure 3). The results suggested that the increases in HTH and HTD had a negative effect on maize production. In the S3H region, an increase in HTH by 1 h corresponded to a decrease of 0.54–1.13% in yield, and a 1 °C increase in HTD corresponded to a 1.34–4.29% decline in yield, whereas in the N3H region, a 1 h increase in HTH corresponded to a decrease of 0.17–0.89% in yield, while a 1 °C increase in HTD corresponded to a 0.21–0.71% decline in yield. In summary, the high-temperature events have a greater impact on the summer maize yield in the S3H region than in the N3H region.

Figure 3. Summary of panel data analysis coefficients showing the estimated sensitivity to changes in high-temperature hours (HTH, +1 h) and high-temperature degrees (HTD, +1 °C) for summer maize in terms of estimated yield changes. S3H, N3H, and 3H indicate the southern Huang-Huai-Hai region, northern Huang-Huai-Hai region, and whole Huang-Huai-Hai region, respectively.

4. Discussion

With climatic warming, the frequency and severity of high-temperature events during the reproductive growth period of crops have increased remarkably, and high-temperature events, as a serious threat to maize production, have been a growing concern [36]. Crops have different optimum and critical temperature thresholds in different development and growth phases; when these thresholds are exceeded, a series of physiological processes associated with yield formation are affected, leading to dramatic yield losses [17]. In fact, many studies have reported on the impact of high temperatures around the flowering period on maize, but information obtained from applying indices of high-temperature events to study their influence on the development and yield of summer maize from heading to maturity in the 3H region is inadequate. We used quantitative methods to estimate the variation characteristics of high-temperature events in recent decades based on phenological and meteorological data from the major summer maize production areas in China. Our results indicated that the intensity of high-temperature events between heading and maturity notably increased during 1980–2016 and that there was a difference in their occurrence frequency between the S3H and N3H regions.

In recent decades, the air temperature across the 3H region during the heading to maturity period of summer maize showed a significant upward trend. T_{min} increased by 0.40 °C per decade, that is, the night-time temperature increased rapidly and the variation trend was mostly consistent with the trend of global climate change [37,38]. Bahuguna et al. [39] found that warmer nights promote night respiration rates and increase the consumption of photosynthate, resulting in decreased biomass. Wang et al. [21] suggested that at the 30 °C night temperature, yield losses mainly result from a decrease in kernel number rather than in kernel weight under high-temperature stress; compared with those in a control treatment, the maize yield and grain number under a warming treatment decreased greatly by 23.8% and 25.1%, respectively.

In this study, we assessed the response of summer maize yield to HTH and HTD by analyzing panel data, and a negative effect on yield caused by the increase in high-temperature events was noted across the S3H and N3H regions. High temperatures above 35 °C in the 3H region usually occur in July and August, but, in this period, the pollination stage of summer maize also occurs. High temperatures prolong the anthesis-silking interval, decrease pollen activity, induce pollen sterility, and inhibit pollen tube growth, which induces yield reduction [19,28]. Additionally, Zhang et al. [27] reported that high temperatures and droughts generally occurred between the tasseling and kernel milk stages in the 3H region in recent decades and the occurrence of high temperatures increases potential evaporation and reduces the supply of soil water [40], which could be another reason for the decline in production. The background temperature of the S3H region was higher than that of the N3H region, and the time trend analysis revealed that the intensity of high-temperature events increased faster in the S3H region, with HTD and HTH increasing by 0.80 °C and 1.30 h per decade, respectively. Consequently, a more severe negative effect on maize yield was recorded in the S3H region than in the N3H region. It should be noted that temperature variability and extreme temperature events will become more prevalent in the future due to the impact of climate change.

The sowing calendar and the crop growth rate affect whether the critical phenology phase coincides with the high-temperature period. Adjusting the sowing date is an important adaptation strategy for avoiding the risks of high temperature and drought during the critical period for maize, ensuring yield and adapting to climate change [41–43]. However, a winter wheat-summer maize rotation system was implemented across most of the 3H Plain. Adjusting the sowing window of summer maize will have an impact on the winter wheat growing season [44]. Yadav et al. [45] suggested that heat-tolerant maize genotypes have higher photosynthetic capacity under heat stress, can better adapt to high-temperature environments, and the yield is less affected by high temperatures. New climate resilient maize showed better adaptability and yield performance than current major commercial varieties under high temperatures, low input, and drought conditions [46,47]. Therefore, selecting and cultivating heat-tolerant summer maize varieties is an effective measure to reduce the damage of high temperatures to maize.

In this study, we used meteorological and yield data from the heading to maturity period of summer maize in the 3H region from 1980 to 2016 to evaluate the impact of high-temperature events on yield. However, crop varieties, soil properties, irrigation management, and cultivation technology are also important limiting factors that contribute to maize yield and yield stability [48,49]. Therefore, to assess the influence of climatic change on crop production more accurately in future studies, these factors should be emphasized and assessed individually.

5. Conclusions

From 1980–2016, both the air temperature and the intensity of high-temperature events during the maize heading to maturity period across the 3H region showed significant upward trends. The increases in HTH and HTD had a negative effect on the summer maize yield in the S3H and N3H regions, but this effect was more severe in the S3H region. Given the uncertainties surrounding climate change and the increase in extreme high temperature events, and considering the close connection between the planting times of winter wheat and summer maize, improving the heat tolerance of maize through variety improvement is an effective strategy for addressing this issue.

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