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Analysis on Heat Characteristics for Summer Maize Cropping in a Semi-Arid Region

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Abstract: Heat stress during flowering is a critical limitation for summer maize production. However, the incidence of heat varies with years and locations, and it poses a great risk to successful maize reproduction and kernel setting. Therefore, it is essential to provide a sound quantification of heat occurrence in relation to maize growth and development. Here, we analyzed the characteristics of heat occurrence based on climate data for over 60 years on Huaibei Plain, China. The effective accumulated temperature showed a slight interannual variation. The average maximum temperature ($\overline{T}_{max}$) during flowering was 32 °C–33 °C, which was approximately 2 °C higher than that over the whole growing season. The probability (P) for the daily T_{max} > 33 °C during flowering was closer to 50% and this maximum temperature ranged between 33 °C and 37 °C. The five levels from normal to extreme heat for T_{max} were defined. Across the six studied sites, the mild level heat stress accounted for most of incidents (P, 25–50%), followed by moderate (P, 13–25%) and severe (P, 0.5–13%), and the minimum for extreme heat stress (P, 0.5%). Four phases bracketing flowering during maize development were given, i.e., 1 week prior to anthesis, 1 week during anthesis, 1 week for anthesis-silking, and 1week post silking. There was a greater probability for heat stress incidents from anthesis to silking compared to the other developmental stages. Additionally, maize grain yield slightly increased with the increase in T_{max} to 33 °C, but it declined as T_{max} surpassed 33 °C. In conclusion, the pattern and characteristics of heat stress were quantified bracketing maize flowering. These findings assist to advise summer maize cropping strategies on the semi-arid and semi-humid Huaibei Plain, China or similar climate and cropping regions.

Keywords: *Zea mays* L.; bracketing flowering; heat stress incidents; cropping risk

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1. Introduction

Maize (*Zea mays* L.), as a staple food, plays an important role in securing food security and is also one of the most important cereal crops as a source of feed and industrial raw material for humans and animals [1–3]. However, maize production is subject to increasing risk of heat stress because of climate change [4]. The average temperature has risen by 0.46 °C from the preindustrial period to the 1971−2000 period [5], and the increasing trend of temperature may continue during the 21st century [6,7]. In addition to the increased global surface temperature, the occurrence frequency and intensity of heat stress are also increasing significantly [8,9]. It is reported that a short duration of heat stress during the critical flowering stage can lead to a huge yield loss caused by heat-induced reproductive failure [10]. Thus, heat stress during flowering has become one of the major meteorological disasters for maize cropping [6,11].

Heat stress during the flowering interferes in a series of events such as tasseling, pollen shedding, silking, pollination, pollen germination, pollen tube growth, and fertilization [12–14]. It is reported that in the pre-anthesis phase (7 days before pollination) heat accelerates tasseling and heat during anthesis phase reduces pollen shedding time, impairs pollen morphology, and induces pollen sterility [15–17]. In addition, high temperature at the silking phase inhibits anther dehiscence [18,19], pollen germination, and pollen tube extension [20]. Furthermore, post-silking (15 days) heat hinders fertilization and kernel development [20,21], which finally leads to a decrease in the seed-setting rate and grain yield [4,14]. Heat stress during different developmental phases variably affects maize reproductive growth; therefore, it is critical to quantify the occurrence characteristics of heat stress during these different phases, i.e., pre-anthesis, anthesis, silking, and post-silking.

Huaibei Plain in North Anhui, located at the south of Huang-Huai-Hai Plain in China, is one of the major areas under maize production in Anhui Province [22]. A rotation system with summer maize sown in early June and winter wheat sown in early October was commonly adopted on the Huaibei Plain over last many decades and is likely to continue for the next decade [18,23]. As such, maize flowering normally occurs in late July or early August in this region, which often coincides with heat incidence [24,25]. It is reported that the frequency of heat stress was approximately once in every 1.7 years on Huaibei Plain [24]. The frequency of moderate and severe heat stress during maize flowering was higher than 15% and 20%, respectively [24]. In addition, the number of days, timing, duration, and severity of heat events are becoming more frequent under global warming [26]. Therefore, it is necessary to quantify the characteristics of heat stress with reference to maize flowering, to provide guidelines for maize-cropping systems.

However, the characteristics of heat stress occurrence on Huaibei Plain or nearby regions are rarely analyzed. In particular, heat occurrence analysis in relation to the specific maize flowering stage is not reported. Therefore, the objective of this study is to quantify the spatiotemporal characteristics of heat stress occurrence with reference to the critical period bracketing maize flowering based on the historical meteorological data from six sites on Huaibei Plain, China.

2. Materials and Methods

2.1. Study Area and Data Sources

Six sites, i.e., Shouxian (116.78° E, 32.55° N, south on the map), Bengbu (117.38° E, 32.92° N, east on the map), Fuyang (115.82° E, 32.90° N, west on the map), Suzhou (116.98° E, 33.63° N, northeast on the map), Bozhou (115.78° E, 33.85° N, northwest on the map), and Dangshan (116.35° E, 34.42° N, north on the map) were chosen on Huaibei Plain, Anhui Province, China (Figure 1). Daily maximum temperature (T_{max}), minimum temperature (T_{min}), and mean temperature (T_{mean}) data around maize growing season and flowering stage were obtained from the China Meteorological Data Service Centre (CMDC, http://data.cma.cn/, accessed on 7 January 2016). Maize grain yield data are only available from 1998 to 2017 at the four sites, i.e., Fuyang, Bozhou, Suzhou, and Bengbu, since in earlier years no such detailed online records were available in the local agricultural bureau.

Maize-cropping characteristics are based on typical local farming practices, i.e., sowing around mid–early June, anthesis to silking around late July to early August, and harvested by the end of September or early October [23,27]. Critical developmental stages bracketing flowering usually occurred from 15 July to 15 August (32 days) in this region or nearby.

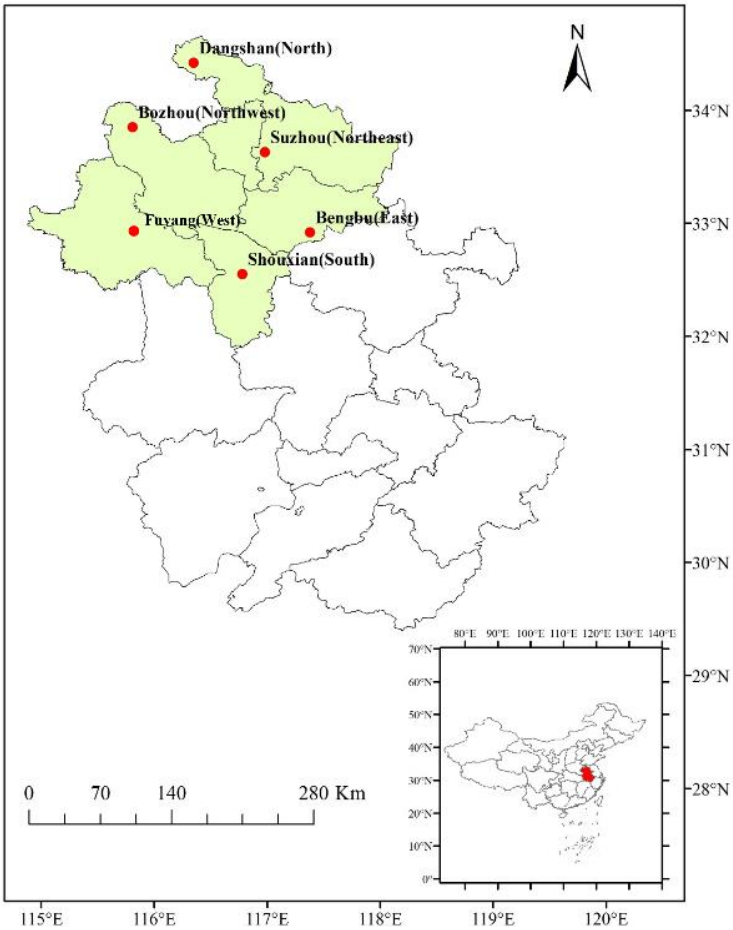

Figure 1. The locations of Shouxian (south, 116.78° E, 32.55° N), Bengbu (east, 117.38° E, 32.92° N), Fuyang (west, 115.82° E, 32.90° N), Suzhou (northeast, 116.98° E, 33.63° N), Bozhou (northwest, 115.78° E, 33.85° N), and Dangshan (north, 116.35° E, 34.42° N) on Huaibei Plain, North Anhui Province, China.

2.2. Data Analysis during Maize Growing Season and Flowering Stage over 61 Years (1957–2017)

The effective accumulated temperature referred to the sum of daily temperatures with a base temperature of 8 °C was quantified during the summer maize growing season across the six sites. The characteristics of average annual maximum temperature ($\overline{T}_{max}$), minimum temperature ($\overline{T}_{min}$), and mean temperature ($\overline{T}_{mean}$), and its coefficient of variation (CV) value were analyzed for both the entire maize growing season and for the flowering stage for the six sites.

A threshold temperature of 33 °C is reported to induce heat stress during maize flowering [28,29] and is selected for this study. First, the number of days with daily T_{max} lower than, greater than, or equal to 33 °C were counted over the 32-day period around flowering, and the probability of the number of days for T_{max} < or ≥ 33 °C were determined. Furthermore, from 33 °C to 40 °C, the occurrence of days with T_{max} higher than specific thresholds were calculated (hereafter, heat days, HD).

According to classification standards issued by the China Meteorological Administration (CMA, http://www.cma.gov.cn/en2014/, accessed on 20 March 2012), the heat stress warnings fall into three levels, i.e., (i) yellow warning signal, when $T_{max} \geq 35$ °C for two consecutive days; (ii) orange warning signal, when $T_{max} \geq 37$ °C for one day; (iii) red warning signal, when $T_{max} \geq 40$ °C for one day. Then the occurrence probability of heat stress duration days (DDs, form ≥1 d to ≥7 consecutive days) and heat stress warning were calculated. The five levels for daily maximum temperature i.e., I (normal), II (mild), III (moderate), IV (severe) and V (extreme) were classified based on T_{max}, duration days

(DDs), occurrence probability (OP, %), and warning color (WC) (Table 1). Moreover, the 32-day period (from 15 July to 15 August) around flowering was divided into four phases: pre-anthesis (A, from 15 to 24 July), anthesis (B, from 25 to 31 July), silking (C, from 1 to 7 August), and post-silking (D, from 8 to 15 August). The probability of heat stress occurrence was analyzed in each phase with different temperature thresholds. Finally, the daily T_{max} average in each phase were extracted to investigate the distribution of the heat events over years. A heat map was generated to represent the detailed characteristics of the heat events over time across various sites.

Table 1. Classification and criteria for heat stress on Huaibei Plain, China.

Level	Classification	Maximum Temperature (T_{max})	Duration Days (DDs)	Occurrence Probability (OP, %)	Warning Colour (WC)
I	Normal	T_{max} < 33 °C	DDs ≥ 1	P > 50	Green
II	Mild	33 °C ≤ T_{max} < 35 °C	DDs ≥ 1	25 < P ≤ 50	Reseda
III	Moderate	35 °C ≤ T_{max} < 37 °C	DDs ≥ 2	13 < P ≤ 25	Yellow
IV	Severe	37 °C ≤ T_{max} < 40 °C	DDs ≥ 1	0.5 < P ≤ 13	Orange
V	Extreme	T_{max} ≥ 40 °C	DDs ≥ 1	P ≤ 0.5	Red

2.3. Inverse Distance Weighting Method Quantifies the Spatial Distribution of Heat Stress Occurrence Probability

The inverse distance weighting (IDW) [30] method is one of the most widely used deterministic methods in spatial interpolation, which is characterized by high speed, convenient computation, and interpretation. IDW sums the values of nearby points multiplied by a weighting factor that is a decreasing function of distance. For this operation, ArcGIS 10.2 software (Environmental Systems Research Institute (ESRI) Inc., Redlands, CA, USA) was used to quantify spatial distribution of heat stress occurrence probability on Huaibei Plain.

2.4. Relationship between Maize Grain Yield and Average Daily T_{max} around Maize Flowering in 1998–2017

Climate change has had bidirectional effects on maize production over the past 20 years on Huang-Huai-Hai Plain (including Huaibei Plain) [31]. The optimal temperature for maize plants in daytime ranges from 22 to 32 °C [32], while the temperature above 33 °C does harm to maize production during flowering [28,29]. The relationship of maize grain yield and the average daily T_{max} in each phase, i.e., pre-anthesis from 15 to 24 July, anthesis from 25 to 31 July, silking from 1 to 7 August, and post-silking from 8 to 15 August, was conducted using the recent 20 years of data (from 1998 to 2017, except for 2003, as the record is missing because of extreme meteorological disasters at four sites, i.e., Bengbu, Fuyang, Suzhou, and Bozhou. Then, the data were analyzed with the relationship between maize grain yield and T_{max} < 33 °C and T_{max} ≥ 33 °C embedded in Microsoft Office Excel (Microsoft Excel 2016, Microsoft, Redmond, WA, USA) software.

3. Results

3.1. Interannual Variation of Effective Accumulated Temperature during Maize Growing Season

The interannual variation of effective accumulated temperature during the summer maize growing season over years across the six sites ranged from 1800 °Cd to 2200 °Cd (Figure 2), with the highest of 2215.8 °Cd at Bengbu, and the lowest of 1800.8 °Cd at Dangshan. In addition, CV values, as an index reflecting the fluctuation degree of effective accumulated temperature between years, were relatively small for the six sites and ranged from 3.85% in Shouxian to 4.16% in Suzhou, indicating that the interannual variation of effective accumulated temperature during maize growing season was relatively stable.

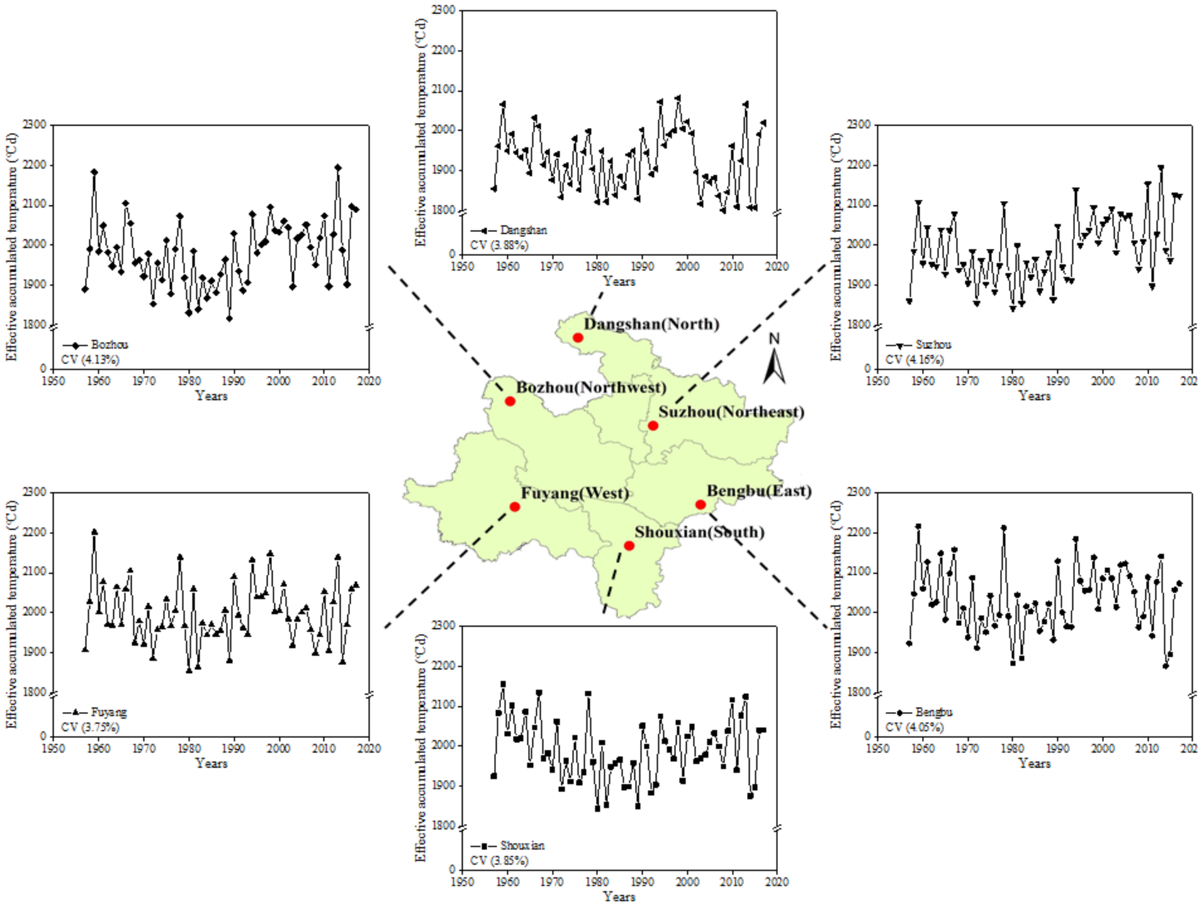

Figure 2. Interannual variation of effective accumulated temperature from 10 June to 30 September corresponding to the summer maize growing season in the past 61 years (1957–2017) for six sites, i.e., Shouxian, Bengbu, Fuyang, Suzhou, Bozhou, and Dangshan, on Huaibei Plain, China.

3.2. The Characteristics of $\overline{T}_{max}$, $\overline{T}_{min}$, $\overline{T}_{mean}$ and CV Value during Maize Growing Season and Flowering Stage

The characteristics of $\overline{T}_{\text{max}}$, $\overline{T}_{\text{min}}$, $\overline{T}_{\text{mean}}$ are shown during maize growing season and the flowering stage by working out the average of data of 61 years of the study sites (Table 2). Approximately $\overline{T}_{\text{max}}$ of 33 °C was calculated for the entire growing season, and $\overline{T}_{\text{max}}$ around the flowering stage ranged from 32 °C to 33 °C. The $\overline{T}_{\text{min}}$ and $\overline{T}_{\text{mean}}$ also showed similar characteristics for these periods, that is, the average temperature at flowering stage was approximately 2 °C higher than that of the entire growing season. The CV for different developmental phases and sites varied between 2.6% and 4.5% (Table 2). The results showed that average temperature during the flowering stage was relatively higher than that of the growing season, and the stable interannual temperature variation may be the reason for the minor fluctuation of effective accumulated temperature during the maize growing season.

Table 2. Quantitative of characteristics of $\overline{T}_{max}$ (°C), $\overline{T}_{min}$ (°C) and $\overline{T}_{mean}$ (°C) and its CV (%) value during the maize growing season and flowering stage over 61 years in six sites, i.e., Shouxian, Bengbu, Fuyang, Suzhou, Bozhou, and Dangshan.

Period	Sites	$\overline{T}_{max}$, °C (CV, %)	$\overline{T}_{min}$, °C (CV, %)	$\overline{T}_{mean}$, °C (CV, %)
Growing season	Shouxian	29.97 (3.23)	22.01 (2.88)	25.61 (2.65)
	Bengbu	30.48 (3.23)	22.30 (3.08)	25.98 (2.78)
	Fuyang	30.46 (3.06)	21.79 (2.78)	25.66 (2.61)
	Suzhou	30.41 (2.81)	21.73 (3.81)	25.62 (2.86)
	Bozhou	30.51 (2.82)	21.42 (3.83)	25.52 (2.84)
	Dangshan	30.09 (2.65)	20.99 (3.27)	25.04 (2.64)
Flowering stage	Shouxian	32.31 (4.44)	24.73 (3.15)	28.15 (3.59)
	Bengbu	32.94 (4.52)	25.08 (3.24)	28.59 (3.78)
	Fuyang	32.67 (4.23)	24.52 (3.20)	28.16 (3.61)
	Suzhou	32.48 (3.99)	24.47 (3.72)	28.02 (3.59)
	Bozhou	32.44 (3.89)	24.17 (3.75)	27.87 (3.62)
	Dangshan	31.96 (3.64)	23.86 (3.68)	27.42 (3.51)

3.3. The Spatial Distribution of Probability for Days in 32-Day Period with T_{max} ≥ 33 °C

Figure 3 shows the spatial distribution of probability with T_{max} ≥ 33 °C over 61 years on Huaibei Plain. The probability for T_{max} ≥ 33 °C was estimated as 44.6% for Shouxian, 52.2% for Bengbu, 49.6% for Fuyang, 45.1% for Suzhou, 45% for Bozhou, and 38.3% for Dangshan (Figure 3). This suggested that T_{max} ≥ 33 °C occurred for nearly half of the time during the flowering phase of the crop (32-day period). Consequently, it causes a high risk for a maize crop, exposing it to heat stress events in this region.

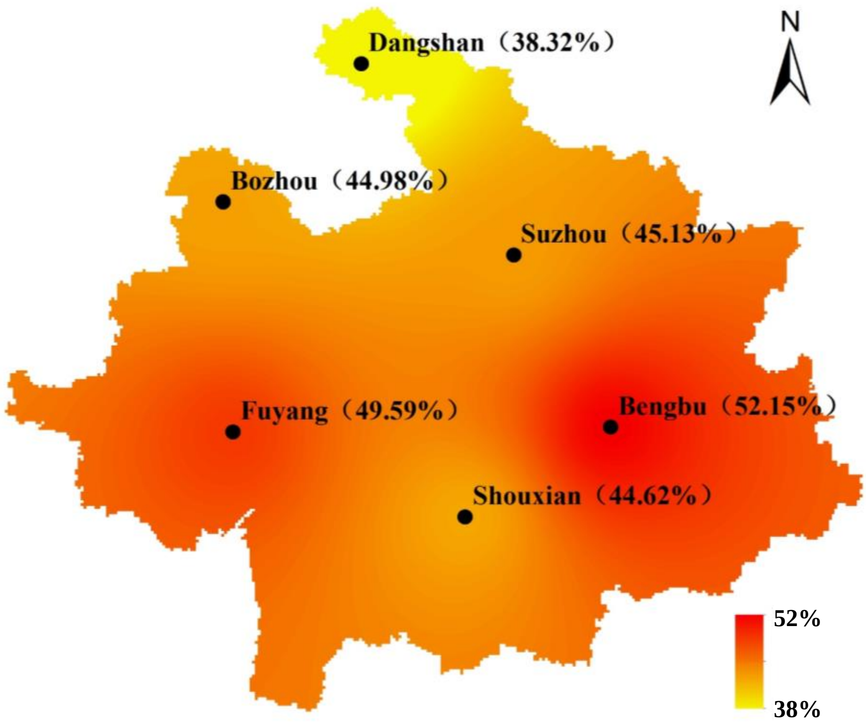

Figure 3. The Spatial distribution of probability for days with T_{max} ≥ 33 °C during the flowering stage in six sites, i.e., Shouxian, Bengbu, Fuyang, Suzhou, Bozhou, and Dangshan, on Huaibei Plain, China.

3.4. The Occurrence Frequency of HDs

Within the 32 days bracketing flowering, the occurrence of days with T_{max} between 33 and 40 °C are shown in Figure 4. As T_{max} increased, the days corresponding to T_{max} gradually decreased across all the sites. When the temperature threshold reached 39–40 °C, the number of days were close to zero. The fitted T_{max}–day curve showed that the HDs decline slowly, followed by dropping quickly, and lastly plateaued as the temperature increased. Most of the HDs occurred between 33–37 °C (Figure 4), but there were considerable spatial variations across the sites.

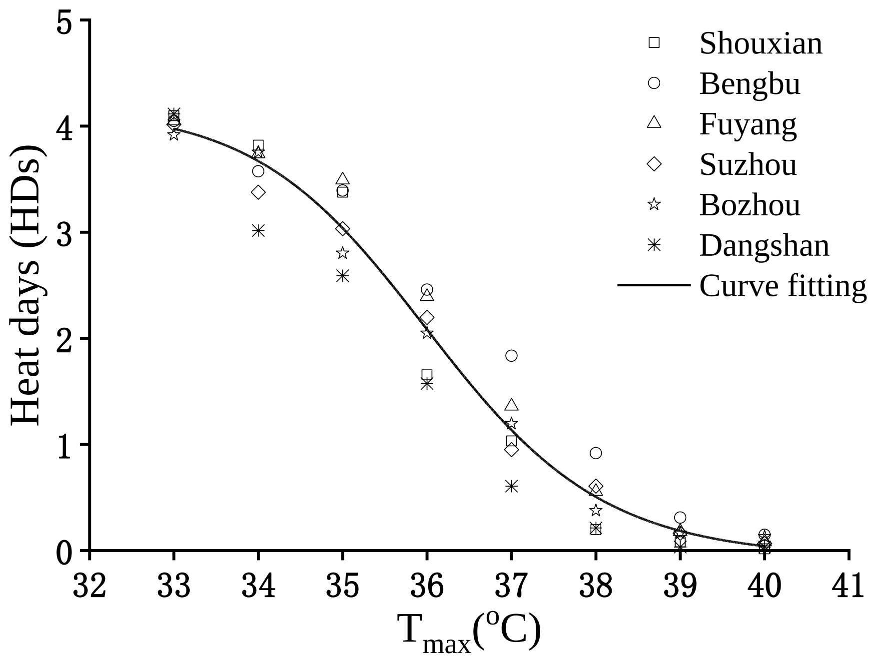

Figure 4. The occurrence frequency and curve fitting of days with T_{max} greater than the specified temperature thresholds during the flowering stage for six sites, i.e., Shouxian (square), Bengbu (circle), Fuyang (triangle), Suzhou (rhombus), Bozhou (pentacle), and Dangshan (asterisk), on Huaibei Plain, China.

3.5. The Occurrence Probability and Classification of Heat Events

The continuous sustained high temperature, particularly during the maize flowering stage, significantly damages the crop yield. Thus, we quantified the occurrence probability of DDs at different temperature thresholds. There was a 50% chance for T_{max} ≥ 33 °C occurring for at least one day during flowering. With higher thresholds and longer DDs, the probability of heat stress decreased, but the probability of heat stress from ≥33 °C to ≥35 °C was still very high (Table 3). In addition, the occurrence probability of moderate (yellow warning) and severe (orange warming) heat stress was 25% and 10%, respectively. For the extreme heat of the red warning, the probability was estimated to be less than 0.5%, suggesting that heat events of ≥40 °C have rarely occurred in the region (Table 3).

Heat events around maize flowering were classified into four phases (A, B, C, and D) based on T_{max} and OP over the years across the six studied sites, as described in the previous section in detail. At T_{max} ≥ 33 °C, the OP of heat stress in four phases was about 30% (28.5% in D phase in Dangshan) to 60% (60.9% in B phase in Bengbu), which gradually decreased as the temperature threshold increased. The OP was always highest during phase B between T_{max} ≥ 33 °C to 36 °C and lowest during phase D compared with all other phases (Table 3). The OP of heat stress in each phase was highest for Bengbu and the lowest for Dangshan. The results showed that heat stress was more likely to occur at anthesis–silking compared to the other phases during flowering. However, HDs with T_{max} ≥ 37 °C have been more likely to occur in phase A (Table 4).

Table 3. The occurrence probability (%) of duration days (DDs) from 1 day to over 7 consecutive days and heat stress warnings during the flowering stage in six selected sites, i.e., Shouxian, Bengbu, Fuyang, Suzhou, Bozhou, and Dangshan, on Huaibei Plain, China.

T_{max}	Shouxian							Bengbu							Fuyang						
	≥1 d	≥2 d	≥3 d	≥4 d	≥5 d	≥6 d	≥7 d	≥1 d	≥2 d	≥3 d	≥4 d	≥5 d	≥6 d	≥7 d	≥1 d	≥2 d	≥3 d	≥4 d	≥5 d	≥6 d	≥7 d
≥33 °C	44.6	41.3	37.6	32.4	29.5	25.9	24.7	52.2	48.9	45.1	40.2	35.9	31.8	30.0	49.6	45.7	42.7	39.2	34.5	31.7	27.0
≥34 °C	31.9	29.0	25.5	22.1	18.8	15.0	13.1	39.7	36.3	33.0	28.0	24.5	20.4	18.9	37.0	33.8	30.9	26.4	23.2	18.8	16.3
≥35 °C	20.0	17.4	15.3	13.0	11.0	8.1	6.9	28.4	25.7	22.7	18.5	14.9	11.8	11.2	25.3	22.7	19.9	15.8	12.7	9.6	8.7
≥36 °C	9.4	7.2	5.9	4.3	3.8	3.1	3.1	17.9	16.0	13.7	10.6	8.1	7.6	6.4	14.0	11.7	9.5	7.1	6.3	5.0	3.4
≥37 °C	4.2	3.1	2.5	1.9	1.9	1.6	1.0	10.1	8.9	7.2	5.6	5.2	4.5	2.9	6.9	5.6	4.5	3.2	3.0	2.3	1.9
≥38 °C	0.9	0.5	0.5	0.3	0.3	0.3	0.0	4.3	3.3	2.2	1.9	1.5	1.2	0.9	2.7	1.7	1.3	1.3	0.9	0.4	0.4
≥39 °C	0.3	0.2	0.2	0.2	0.0	0.0	0.0	1.4	1.1	1.0	0.7	0.3	0.0	0.0	0.8	0.4	0.3	0.3	0.3	0.0	0.0
≥40 °C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.3	0.3	0.3	0.0	0.0	0.3	0.2	0.2	0.2	0.0	0.0	0.0
T_{max}	Suzhou							Bozhou							Dangshan						
	≥1 d	≥2 d	≥3 d	≥4 d	≥5 d	≥6 d	≥7 d	≥1 d	≥2 d	≥3 d	≥4 d	≥5 d	≥6 d	≥7 d	≥1 d	≥2 d	≥3 d	≥4 d	≥5 d	≥6 d	≥7 d
≥33 °C	45.1	41.5	37.8	34.0	29.7	25.8	24.0	45.0	41.0	36.8	32.1	27.8	23.9	21.8	38.3	34.4	29.7	24.5	20.8	18.8	16.0
≥34 °C	32.6	29.8	26.8	22.4	17.1	15.0	12.9	32.8	30.0	25.9	21.6	17.9	15.9	13.7	25.4	22.2	17.6	14.5	10.9	8.6	7.3
≥35 °C	22.2	19.7	16.0	12.9	9.4	8.7	7.1	21.1	18.5	15.0	12.3	9.3	8.0	6.8	15.9	13.1	10.8	8.6	5.5	4.8	3.8
≥36 °C	12.7	10.0	8.4	7.1	5.5	4.7	4.4	12.4	9.8	7.6	6.4	5.3	4.8	3.3	7.9	5.6	4.0	2.6	2.2	1.4	1.1
≥37 °C	5.7	4.5	3.3	2.9	2.3	2.0	1.1	5.9	4.5	3.5	2.6	2.2	1.4	0.8	2.8	1.9	1.2	0.9	0.5	0.0	0.0
≥38 °C	2.6	2.3	1.7	1.3	1.1	0.3	0.0	2.2	1.6	1.0	0.7	0.5	0.0	0.0	0.9	0.5	0.5	0.2	0.0	0.0	0.0
≥39 °C	0.7	0.5	0.2	0.2	0.0	0.0	0.0	1.0	0.9	0.6	0.4	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.0	0.0	0.0
≥40 °C	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.3	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0

Table 4. The occurrence probability (%) of heat stress in four phases, i.e., pre-anthesis (A, 15–24 July), anthesis (B, 25–31 July), silking (C, 1–7 August), and post-silking (D, 8–15 August), around maize flowering in six selected sites, i.e., Shouxian, Bengbu, Fuyang, Suzhou, Bozhou, and Dangshan, on Huaibei Plain, China.

T_{max}	Shouxian				Bengbu				Fuyang				Suzhou				Bozhou				Dangshan			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
≥33 °C	43.6	54.1	46.8	35.7	52.1	60.9	54.3	42.6	49.5	59.5	48.7	41.8	45.1	53.2	45.2	38.1	46.6	51.1	44.7	37.9	39.8	45.4	40.3	28.5
≥34 °C	33.1	38.9	34.2	21.9	40.5	47.3	42.2	29.3	39.5	42.2	39.1	27.0	35.6	39.3	33.3	22.1	36.4	38.9	32.6	23.0	28.7	31.4	26.0	15.2
≥35 °C	21.5	24.6	21.3	12.5	30.5	35.4	29.5	18.6	27.9	30.4	27.2	15.6	24.3	27.6	24.6	12.5	24.3	26.7	22.0	11.3	18.7	21.5	17.3	5.7
≥36 °C	10.5	12.2	8.2	6.4	21.8	22.2	18.0	9.0	18.2	16.6	15.2	6.4	15.2	16.2	13.3	5.9	15.2	16.4	12.6	4.9	10.5	10.1	6.8	2.9
≥37 °C	4.6	5.4	3.5	3.1	13.1	11.9	10.3	4.5	9.5	7.5	6.6	3.3	7.4	7.5	4.2	3.3	8.4	6.6	5.4	2.5	4.3	2.1	2.8	1.4
≥38 °C	1.0	1.6	0.5	0.6	5.6	4.4	4.4	2.5	3.3	2.8	2.1	1.8	4.3	3.3	1.2	1.2	3.8	1.6	2.1	0.8	1.3	0.7	0.9	0.4
≥39 °C	0.2	1.2	0.0	0.0	2.0	1.2	1.6	1.2	1.1	0.7	0.5	0.4	1.5	0.7	0.5	0.0	1.6	0.7	0.9	0.4	0.5	0.0	0.2	0.0
≥40 °C	0.0	0.2	0.0	0.0	0.5	0.7	0.7	0.4	0.2	0.2	0.2	0.0	0.5	0.2	0.0	0.0	0.8	0.7	0.0	0.0	0.3	0.0	0.0	0.0

3.6. The Occurrence, Intensity, and Distribution of Heat Events over Four Phases, i.e., Pre-Anthesis (A), Anthesis (B), Silking (C), and Post-Silking (D)

The heat map shows the occurrence, intensity, and distribution of heat events at pre-anthesis (A), anthesis (B), silking (C), and post-silking (D) over the years across the studied sites (Figure 5). The mild heat events occurred frequently across the four phases during the last 61 years, while extreme heat events rarely occurred across the six locations. Furthermore, the studied 61-year period was divided into three successive periods: first 20 years (1957–1976), second 20 years (1977–1996), and last 21 years (1997–2017). During the first 20 years, mild and moderate heat stress occurred frequently during the four phases, with a low frequency of occurrence of severe and extreme heat stress (Figure 5I), but, in the second period, the normal situation (no heat stress), and mild and moderate heat stress occurred occasionally (Figure 5II). In the last 21-year period, the mild to moderate heat stress occurred often, and moderate to severe heat stress occurred at times, especially between 2010 and 2017, particularly during anthesis (Figure 5III). It should be noted that extreme heat stress could possibly occur at any of the four phases in different years and sites. This suggested that climate change could lead to more uncertain extreme heat events.

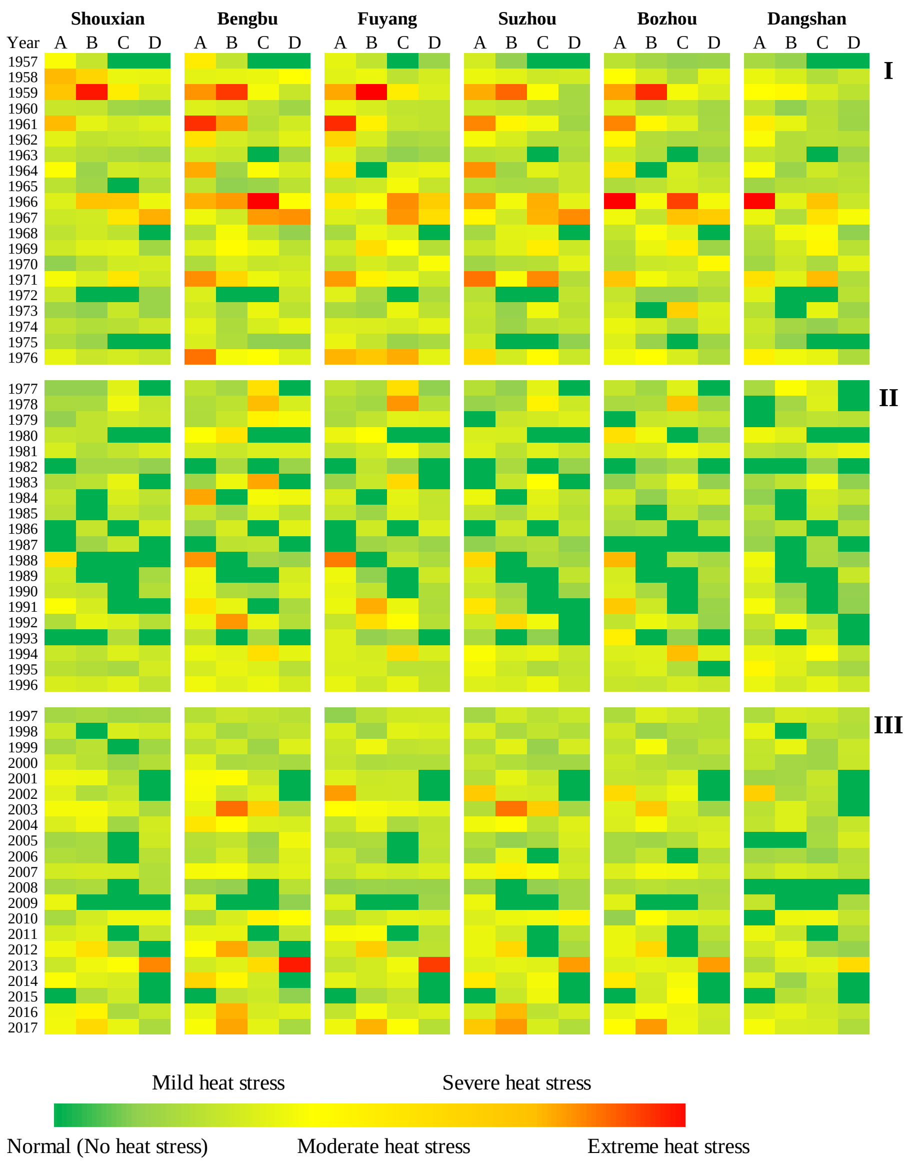

Figure 5. The occurrence, intensity, and distribution of heat events in three successive phases of the

first 20 years (**I**, 1957–1976), second 20 years (**II**, 1977–1996), and last 21 years (**III**, 1997–2017) in four phases (A, pre-anthesis; B, anthesis; C, silking; and D, post-silking) at six sites, i.e., Shouxian, Bengbu, Fuyang, Suzhou, Bozhou, and Dangshan, on Huaibei Plain, China. Note: green color indicates no heat stress; reseda color indicates mild heat stress; yellow color indicates moderate heat stress; orange color indicates severe heat stress; and red color indicates extreme heat stress.

3.7. Relationship between Maize Grain Yield and Average Daily T_{max} around Maize Flowering

The relationship between maize grain yield and average daily T_{max} around flowering for the last 20 years was calculated (Figure 6). The average maize grain yield ranged between 4–6 t ha^{-1} at different average daily T_{max}. Specifically, grain yield slightly increased as the T_{max} increased up to 33 °C (R^2 from 0.0006 to 0.4528), while it declined as the T_{max} surpassed 33 °C (R^2 from 0.001 to 0.3957), except for in Fuyang and Suzhou at the silking phase, indicating that with the bidirectional impact of increasing temperature on maize production over the past 20 years on Huaibei Plain, the trends below and above 33 °C are not significant. Therefore, T_{max} around 33 °C may be a temperature threshold for maize production. Maize grain yield negatively responds to the increase in T_{max} during flowering, and the higher the T_{max} threshold was, the more significantly did the grain yield decline.

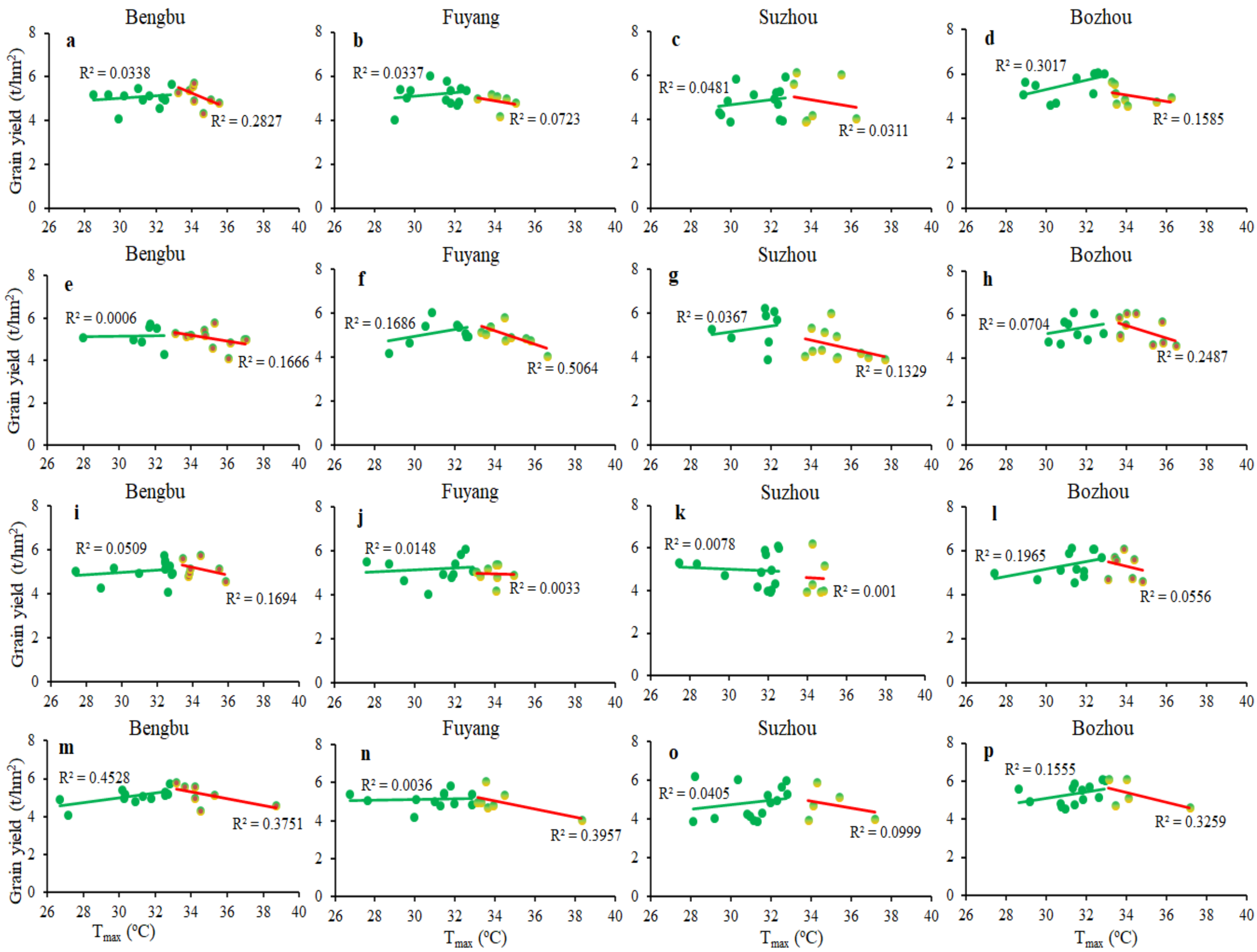

Figure 6. The relationship and linear fitting between maize grain yield and T_{max} during flowering stage, including four phases, i.e., pre-anthesis (from 15 to 24 July, top subfigure layer), anthesis (from

25 to 31 July, upper-middle subfigure layer), silking (from 1 to 7 August, lower-middle subfigure layer), and post-silking (from 8 to 15 August, bottom subfigure layer) at four sites, i.e., Bengbu (**a**,**e**,**i**,**m**), Fuyang (**b**,**f**,**j**,**n**), Suzhou (**c**,**g**,**k**,**o**), and Bozhou (**d**,**h**,**l**,**p**), on Huaibei Plain, China. Note: green and red lines represent fitting of the relationship between maize grain yield and average daily T_{max} < and ≥ 33 °C, respectively. Green and light green dots represent maize grain yield under average daily T_{max} < and ≥ 33 °C, respectively.

4. Discussion

4.1. The Characteristics of Heat Risk Occurrence over Years in Huaibei Plain, China

With a warming climate, heat events occur more frequently, especially during maize flowering [26], and the average maximum temperature (T_{maxx}) during the flowering stage was consistently higher than that of the entire growing season. The comprehensive occurrence frequency of heat stress of summer maize on Huaibei Plain was relatively high, and the occurrence frequency of extreme heat stress was about 8% [24]. In this study, the probability of heat stress is estimated to be close to 50%, and the occurrence frequency of mild, moderate, severe, and extreme heat events was about 50%, 25% to 50%, 0.5% to 13%, and less than 0.5%, respectively, indicating that heat stress occurred once every 2 years, with a frequent occurrence of T_{max} ≥ 33 °C and T_{max} ≥ 35 °C and occasional occurrence of T_{max} ≥ 37 °C. This difference in the occurrence frequency and probability of heat stress is due to varying temperature threshold classification criteria. In further study, remote sensing data can be used as the data source, which can better reflect the heat stress of the study area compared with the calculation of spatial distribution of high temperature based on meteorological point data [33].

Globally, the occurrence intensity and frequency of heat stress events are increasing significantly [9,34], but there was little information on how the number of heat days (HDs) varies with temperature. In this study, the number of HDs showed a slow decline, followed by a quick drop, and lastly it plateaued with increases in temperature, and the most HDs occurred between 33 °C and 37 °C. In addition, heat stress during the maize flowering stage has been estimated using different methods and indicators such as extreme degree days, daily relative humidity, and seasonal rainfall [8,24,25]. The grades of heat stress were divided into slight, moderate, and server levels in terms of the occurrence time and duration of heat stress [24,34]. The heat stress classification criteria proposed in this paper comprehensively considered the T_{max}, DDs, OP, and WC, and it is more suitable for the quantification of heat stress characteristics. Furthermore, our study suggested the high probability of heat stress occurrence during anthesis to silking compared to other stages, indicating heat stress has a potential adverse effect on maize anther dehiscence and pollen vigor. The findings showed the onset and duration of heat stress, as well as the level and frequency of its occurrence, which can provide critical information to local farmers to accurately manage their crops for heat risk occurrence.

4.2. Effect of Heat Risk on Rainfed Maize Cropping in Huaibei Plain, China

The effect of heat stress on maize flowering varies with thresholds. In particular, prolonged exposure to temperatures above 32 °C can reduce pollen viability and germination rate to levels down to zero in many genotypes [15]. It is reported that temperatures above 35 °C can greatly reduce ovule fertilization in maize and T_{max} above 36 °C greatly reduced pollen viability [35] because of tapetum layer disintegration [36]. Furthermore, no pollen grain germination was recorded at T_{max} above 38 °C [32], as this temperature inhibits anther dehiscence [18] by reducing anther apical pore width [19]. Maize cropping is extremely sensitive to heat stress during flowering. However, the probability of T_{max} above 33 °C, 35 °C, and 37 °C are about 50%, 20%, and 6% in study area, respectively, so that reproductive processes such as anther dehiscence, pollen number, viability, and germination rate could be affected [4]. In addition, this study shows that heat stress occurred for several consecutive days on Huaibei Plain, such as the probability of seven hot days at above 35 °C was between 3.8% (Dangshan) and 11.2% (Bengbu). This continuous heat stress can further elevate the maize canopy temperature to accelerate tasseling and anthesis, and results in a prolonged anthesis–silking interval (ASI) [14,37,38], which caused great risk to maize production during flowering.

Pre-anthesis heat affects the pollination process by advancing tasseling, accelerating tassel inflorescences, and shifting the duration of pollen shedding [4,14,39], although heat stress has little effect on silk elongation and silking date [4,21] and grain yield remained stable with the T_{max} increases during this phase. When the heat stress coincides with post-silking, the pollen tube growth and pollination and fertilization process were disrupted [17,20,21]. Meanwhile, the frequency of heat events will increase the risk of drought in that they produce positive feedbacks together that intensify their effects [40,41]. Higher temperature may increase potential evapotranspiration, causing more rapid soil drying and greater severity of drought by increasing a vapor pressure deficit [42]. Farmers usually take some additional agronomic measures, i.e., selection of varieties, optimum sowing data, adequate water, fertilizer management, and application of exogenous substances, to adapt to the warmer temperature for reducing the effect of climate change during maize flowering.

4.3. Maize Cropping Strategy for Heat Risk

Climate change is likely to increase the number of hot days and the probability of heat stress around maize flowering on Huaibei Plain [24]. Thus, farmers have to adjust their cropping strategies in response to climate change, particularly via the selection of heat-resistant hybrids and management, such as optimizing the sowing date [43,44], applying a plant growth regulator [45], and improving irrigation systems [46,47]. For example, maize grain yield can be increased by hybrid choices and optimizing sowing dates and cultivar selection under warming of 1.5 °C and 2 °C [11,43]. However, the traditional maize–wheat rotation system dictates a fixed maize sowing time, which is more likely to suffer from heat stress prior to and post flowering, thereby reducing maize yield [48]. Thus, early or late sowing may be possible under warming scenarios [11]. In addition, applying urea in combination with nitrapyrin and plant growth regulator (gibberellic acid) in the pre-flowering stage has the potential to mitigate N_2O emission, improve N response efficiency, and increase maize yield under hot climatic conditions [45]. Moreover, improving irrigation is also an effective means of adaptation for compromising the sensitivity to heat stress by lowering the maize canopy temperature [49]. These agronomic management strategies can effectively alleviate or avoid increased heat stress incidents during maize production.

Crop models have been widely used to provide support, management, and decision-making for maize production [50,51]. For example, the World Food Studies (WOFOST) model and agricultural production systems simulator (APSIM)-maize model were used to simulate sowing dates, cultivar shifts, and climate adaptation for maize cropping, and to predict the potential maize yield based on climate and crop conditions around flowering [52,53]. Therefore, it is feasible to use crop models to predict the occurrence characteristics and countermeasures of heat events under climate change. Notably, the relationship between grain yield and threshold temperature point (33 °C) should be taken into account in model prediction, so as to further analyze the specific climatic suitability and optimize sowing dates and response strategies for heat stress during the maize flowering stage. A schematic diagram of heat stress occurrence patterns, characteristics, and coping strategies of heat risk is provided as Figure 7.

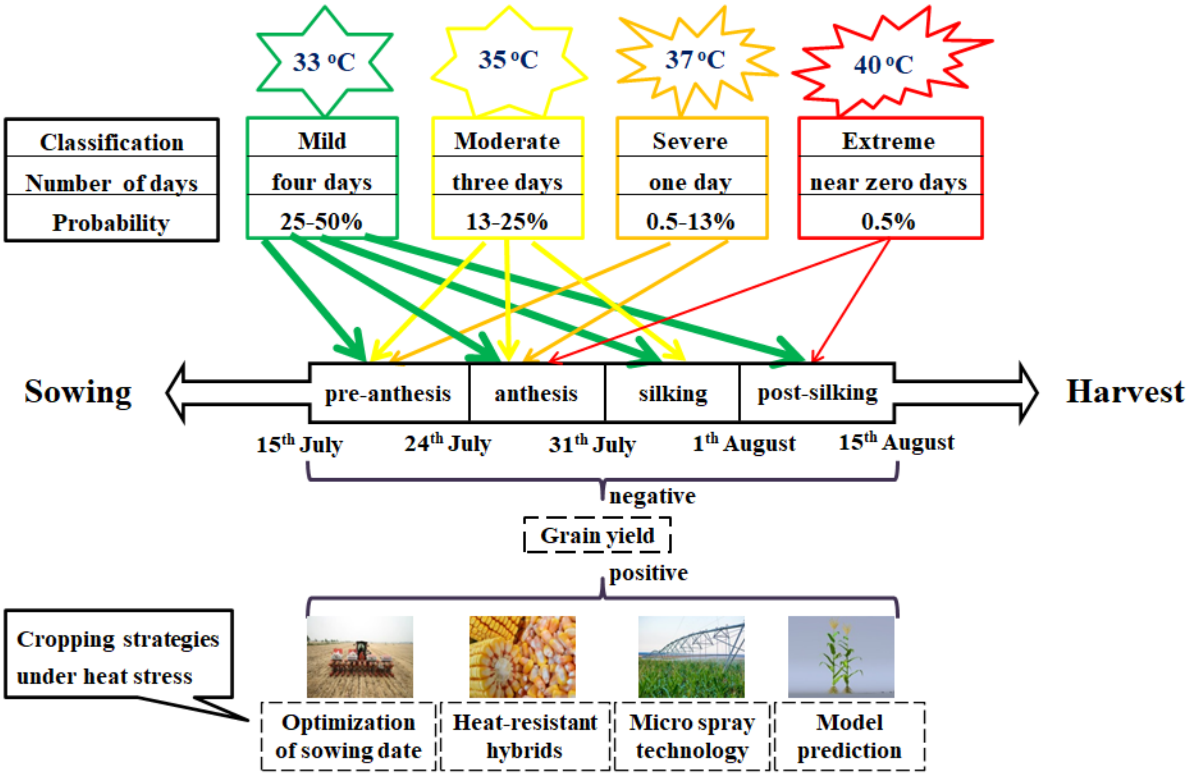

Figure 7. Schematic diagram of occurrence patterns, characteristics, and coping strategies of heat stress in relation to maize cropping on Huaibei Plain, China or similar climate and cropping regions. Note: green, yellow, orange, and red arrow symbols represent mild, moderate, severe, and extreme heat stress, respectively. The thickness and direction of the arrow symbols indicate the probability and phases of the occurrence of heat stress.

5. Conclusions

Heat stress during the maize flowering stage is detrimental for successful maize reproduction and final grain yield formation. In this study, the characteristics of heat stress occurrence in relation to reproductive development were described. The effective accumulated temperature was about 2000 °Cd with little interannual variation. The average maximum temperature (T_{max}) in the flowering stage was about 33 °C, which was higher than that for the entire growing season. The probability of days with $T_{max} \geq 33$ °C is estimated to be 50%, and the most HDs occurred between 33 °C and 37 °C. The five-level classifications of heat stress were identified based on T_{max}, DDs, OP, and WC. In addition, the heat stress for $T_{max} \geq 35$ °C occurred more frequently while the stress for $T_{max} \geq 37$ °C occurred occasionally and for $T_{max} \geq 40$ °C occurred rarely across the studied years and sites. Our study suggested that compared with other phases, heat stress was more likely to occur from anthesis to silking. In addition, the maize grain yield slightly increased as the T_{max} increased to 33 °C, but it declined as the T_{max} surpassed 33 °C, especially in anthesis. These findings will help to guide summer maize cropping under climate change.

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