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Effects of High Temperature and Drought Stresses on Growth and Yield of Summer Maize during Grain Filling in North China

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Abstract: High sensitivity to climate change has been demonstrated in global maize production, especially the extreme high temperature and drought events. At present, the interactive effects of those extreme event stresses on maize growth at the grain filling stage are less well studied. In this study, a two-year field experiment was conducted to evaluate the compound effects of three stressors (high temperature, drought, and stress duration) at the filling phase on phenological period, grain filling rate, yield component, and yield of summer maize. The precipitation and temperature were controlled by using a rain-shelter systems and a warming system with infrared radiation lamps in field plots. The results indicated the significant influences of high temperature, drought stress, and the interaction on the growth and yield of summer maize. Under the individual factor of drought, compared to normal irrigation (NI), the significant decrease in grain-filling rate for mild drought (LD) and severe drought (SD) were 70.7% and 60.6%, respectively, while the decrease in grain yield for LD and SD were 80.1% and 93.6%, respectively. Under the individual factor of temperature, the consequences on grain-filling rate and grain yield were more severe at high temperature (temperature increase by 4.5 °C) than low temperature (temperature increase by 2.3 °C). The compound of high temperature and drought indicated that the grain yield increase by the compound effects of 3 °C for 5 days under normal irrigation (NIT_3D_5) and the compound effects of 3 °C for 7 days under mild drought (LDT_3D7) were 3.5% and 10.9%, respectively, compared to without temperature stress. The grain yields were reduced by the other compound effects. The preferential temperature (temperature increase by 2.3 °C) promoted maize growth under normal irrigation and mild drought, while high temperature (temperature increase by 4.5 °C) significantly inhibited maize growth under normal irrigation and heavy drought. The warming climate is favorable to maize production within certain limits, and will provide a scientific basis for agricultural disaster prevention and mitigation.

Keywords: climate change; drought; high temperature; maize; growth development

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1. Introduction

The frequency and intensity of extreme climate events (heat waves, prolonged droughts, and flooding) have increased across many regions due to global warming [1]. In particular, high temperature and drought have been the main stresses on agricultural production and food security with climate change [2,3]. Multiple indicators of the climate system suggest that more extreme weather events, such as long-term droughts and high temperature, will occur in China as global warming continues [4]. Long-term drought and extreme temperatures escalate the damage caused to plants, ecosystems, and wildlife, which will pose serious challenges to human existence and economic development [5–9]. Recent studies have separately evaluated the effect of droughts and high temperature stresses on agriculture production in China, based on both observations and climate model simulations [10]. However, due to the uncertainties in the climate change impact assessment, current research on the effects of drought and high temperature stresses on crop production was inconsistent [11]. Previous studies have shown that compound effects of extreme climate events on crop growth at different growth stages differed between various crops and regions [12]. Furthermore, the effect of compound events (drought and high temperature) on crop production during crop growing seasons was generally higher than of individual events [13]. North China is the main maize producing region in China, where high temperatures and droughts often occur during the growing season of maize [14]. Therefore, it is rather necessary to study the effects of drought and high temperature combination stresses on a certain crop within a specific growth period in North China.

Maize is currently one of the most important and widely grown cereal crops worldwide. It is not only an important feed and ration, but also has a wide range of industrial uses [15]. In developing countries, maize is a major source of income for many farmers, and is widely used in the food industry [16]. China is a large country with a wide distribution of maize area, and one of the larger in terms of production and consumption in the world [17]. As the main crop in the North China Plain, maize is predominantly planted in summer, and its planting area and yield account for 30% and 50% of the national crop total, respectively [18]. The frequent occurrence of high temperature and drought events in North China has severely affected maize production [19,20]. Previous studies have shown that drought exposes the maize to water stress and hinders the normal maize growth and grain yield [21]. Climate warming is also expected to induce high temperature stress, and reduce the pollen germination, photosynthetic rate, and production of maize [14]. Some studies have shown that future climate change will increase the probability of reduced yield in China's main maize producing areas under rainfed and irrigated maize production [22]. Overall, high temperature and drought are known to be the two major environmental factors limiting the normal growth and development of maize [22,23].

The maize crop is classified as a C4-plant, and its rate of development and productivity are profoundly influenced by drought stress and high temperature, especially in certain stages of crop growth [24,25]. High temperature or drought affects germination, tiller production, vegetative growth, dry matter production, reproductive development, reproductive processes, grain yield, and grain quality [26–32]. The duration of the grain filling period has been shown to be positively related to maturity, grain weight and yield of maize [13]. However, reproductive processes and grain filling were found to be more sensitive to stresses when compared with vegetative growth and development. The imbalance between the short duration of an extreme event and the impact on the agro-ecosystem, which can be either detrimental or beneficial, has made event-focused agriculture research difficult. The impact on plant growth depends largely on how different components of the system are affected by the intensification of the hydrological cycle [33]. Therefore, it is particularly important to assess the interaction of high temperature and drought on the maize filling period.

Nevertheless, many studies have focused on the impacts of climate variability and extremes on crop productivity. These studies have used various methods, including controlled environment experiments, improved crop models, and statistical approaches. In addition to that, most studies focus on the individual effect of drought or high temperature extremes on crop production through climate model simulations at the laboratory level in China. Whether the information on responses of maize growth to combined extreme stresses during specific stages (especially the filling period) at a field scale is still poorly understood. Therefore, in the context of global climate change, the combined influence of drought and high temperature stresses for the study on maize growth during the filling stage becomes more urgent and important. The objectives of this research were to explore the impact of high temperature and drought interaction on maize yield components, growth, and development processes during the filling period.

2. Materials and Methods

2.1. The Experimental Site

The field experiments were conducted from June to October during two consecutive maize growing seasons (2016 and 2017) at the Gucheng Ecological Environment and Agro-meteorological Experiment Station of the China Meteorological Administration in Baoding City. The experimental station (latitude of 39°08′ N, longitude of 115°40′ E, at an altitude of 15.2 m asl) is located in Baoding City, Hebei Province, North China Plain (Figure 1). The area has a warm temperate continental monsoon climate, with an annual average temperature of 12.2 °C, a mean annual precipitation of 528 mm, and an average annual sunshine duration of 2264 h. The soil type in the experimental site is sandy loam, with 0.98 g/kg total nitrogen, 1.02 g/kg total phosphorus, 17.26 g/kg total potassium, and pH value of 8.1 [34]. The area of each plot was 8 m^2 (2 m × 4 m). A 3 m deep concrete separation wall existed between the plots, to prevent soil moisture from moving sideways.

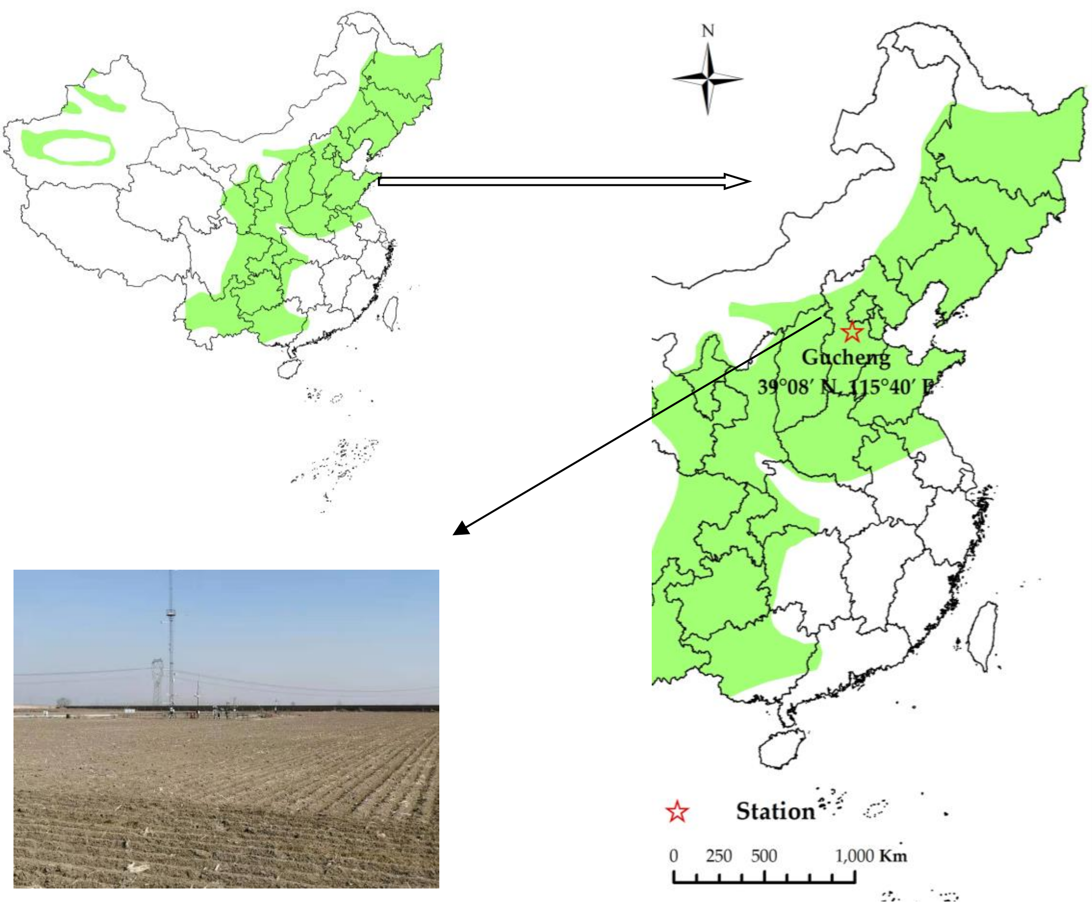

Figure 1. Distribution of geographical location in Gucheng Station (the green shows the maize planting area in China), the red star represent the location of experimental station.

2.2. Experimental Design

2.2.1. Experimental Treatment

Three factors (water stress, amplitude of increasing temperature, and the time of increasing temperature) were set in the experiment during the summer maize filling stage, and a further three levels for each factor were also implemented: water stress was categorized into normal irrigation at 80% field water holding rate (NI), mild drought at 55% (LD), and severe drought at 40% (SD); the temperature increase (all day) gradient was 0 °C (T_0), 3 °C (T_3), and

5 °C (T_5); and the temperature increase time was 0 days (D_0), 5 days (D_5), and 7 days (D_7). The design of the experiment using a three-factor three-level orthogonal method is shown in Table 1, and the experiment treatments were as follows: (1) sufficient irrigation (NI, sufficient moisture), (2) temperature increase by 3 °C for 5 days under sufficient moisture (NIT_3D_5), (3) temperature increase by 5 °C for 7 days under sufficient moisture (NIT_5D_7), (4) Mild drought (LD, ~55% of soil moisture content), (5) temperature increase by 3 °C for 7 days under mild drought (LDT_3D_7), (6) temperature increase by 5 °C for 0 days under mild drought (LDT_5D_0), (7) Severe drought (SD, ~40% of soil moisture content), (8) Temperature increase by 3 °C for 0 days under severe drought (SDT_3D_0), (9) Temperature increase by 5 °C for 7 days under severe drought (SDT_5D_5) (Table 1). Each treatment was randomly arranged with three replicates for a total of 27 plots in all. The temperature increases of the grain filling stage compared to NI is shown in Table 2. Due to temperature increase by 3 °C for 0 days and temperature increase by 5 °C for 0 days meaning without temperature treatment, the LD treatment is the same as the LDT_5D_0 treatment and the SD treatment is the same as the SDT_3D_0.

Table 1. Three-factor three-level orthogonal experiment treatments.

Treatment	Water Stress	Amplitude of Increasing Temperature	Time of Increasing Temperature
NI	NI	T_0	D_0
NIT_3D_5	NI	T_3	D_5
NIT_5D_7	NI	T_5	D_7
LD	LD	T_0	D_5
LDT_3D_7	LD	T_3	D_7
LDT_5D_0	LD	T_5	D_0
SD	SD	T_0	D_7
SDT_3D_0	SD	T_3	D_0
SDT_5D_5	SD	T_5	D_5

Table 2. Temperature increase in the grain filling stage compared to NI.

Year	Temperature Treatment	Air Temp. Increased in Canopy Area (°C)	
		Mean	STDEV
2016	Temperature increase 3 °C	2.26	0.58
	Temperature increase 5 °C	4.45	0.42
2017	Temperature increase 3 °C	2.38	0.53
	Temperature increase 5 °C	4.61	0.61

2.2.2. Experimental Arrangement

The experiment was conducted in the water control experiment field, where the large-scale moveable rain-shelter was prepared to keep off precipitation. Irrigation stage was applied to filled to avoid drought stress as needed. The plots were installed with infrared radiators suspended above the ground as warming devices [35,36]. The warming plots were heated by three stainless steel mirror-reflector infrared radiators suspended 3.0 m above the ground to achieve environmental warming, and its irradiation range only covered the summer maize canopy. All the heaters under warming treatments were set to a radiation output of 2400 W. Compared with the greenhouse and the open-air chamber, the environment of the experimental plot was basically the same as the field conditions. In each control plot, one "dummy" heater with the same shape and size as the infrared heater was used to replace the heater to simulate the shading effect (Figure 2). A set of automatic observation sensors for ground temperature (20 cm) and canopy temperature were installed in each sample plot. Temperature and ground temperature changes were continuously observed once every 10 min.

Figure 2. Layout of instruments in the experimental plot.

2.2.3. Crop Establishment

The field experiment for maize production was conducted during two consecutive years (2016 and 2017). The maize variety Zhengdan 958 was planted in the experimental plot, which is one of the most popular maize hybrids in China. The experimental field's preceding crop was winter wheat with no arable land after harvest. Approximately half a month before sowing, the soil moisture of each plot was measured and then irrigated to the same soil moisture levels in each plot, and the irrigation volume is shown in Table 3.

Table 3. The irrigation volume of treatment/m^3.

	NI	LD (LDT_5D_0)	SD (SDT_3D_0)	NIT_3D_5	NIT_5D_7	LDT_3D_7	SDT_5D_5
2016	0.479	0.323	0.274	0.386	0.352	0.261	0.253
2017	0.481	0.296	0.283	0.412	0.384	0.253	0.268

The maize seeds were sown on 17 June and were well-watered to ensure the emergence of seedlings with 50-cm line spacing and 25-cm row spacing (total plant density of 8.0 plantsm^{-2}). A compound fertilizer was applied at 600 kg·ha^{-1} before sowing each year, and a top dressing of 600 kg·ha^{-1} of urea was applied at the jointing stage, which was equivalent to the fertilization level of the local field. All other agronomic management was implemented according to the local field method in both years.

2.2.4. Field Management

The summer maize for each treatment had normal irrigation in the vegetative growth phase. No more water was added after irrigation in those treatment plots. A large mobile rain shelter was constructed to reduce the risk of rain intrusion after spinning. Normal irrigation treatments were maintained at more than 80% field capacity. Each experiment treatment reached the soil moisture level to be controlled at the beginning of the filling stage. During the filling period on 11 September, the temperature increase was conducted according to the experimental design. The summer maize was no longer sheltered from the rain after the end of the temperature increase, allowing the summer maize to grow in natural conditions.

2.3. Sampling and Measurements

2.3.1. Temperature Observation and Measurements

The canopy temperature and soil temperature at 20 cm depth were recorded using automatic thermometer sensors. Those temperatures were measured at three hour intervals a day. The temperature increases of each treatment is shown in Table 2. The mean air temperature (11–17 September) in the canopy area under the temperature increase of 3 °C was 2.5 °C higher than that under NI. The mean air temperature (11–17 September) in the canopy area under the temperature increase of 5 °C was 4.5 °C higher than that under NI.

2.3.2. Soil Water Content Observations and Measurements

Soil water content was measured using the oven-drying method. The soil water content was measured using the gravimetric method at 10 cm interval to a depth of 100 cm. The samples were weighed both before and after they were dried up in an oven at 105 °C. The relative soil moisture of 0–50 cm depth was used here to describe soil water status. The calculation method for soil water content is detailed in Wang [37]. Soil water content of each treatment before and after temperature increase are shown in Table 4.

Table 4. Soil water relative content (%) before and after temperature increase.

Treatment	2016		2017	
	Before the Temperature Increase	End of Temperature Increase	Before the Temperature Increase	End of Temperature Increase
NI	89.8 ± 2%	87.3 ± 2%	91.5 ± 2%	87.3 ± 2%
NIT_3D_5	91.3 ± 2%	85.7 ± 2%	90.8 ± 2%	84.6 ± 2%
NIT_5D_7	90.6 ± 2%	83.5 ± 2%	91.2 ± 2%	82.5 ± 2%
LD (LDT_5D_0)	50.1 ± 2%	46.8 ± 2%	53.1 ± 2%	47.5 ± 2%
LDT_3D_7	53.5 ± 2%	42.6 ± 2%	55.7 ± 2%	45.9 ± 2%
SD (SDT_3D_0)	44.5 ± 2%	43.9 ± 2%	42.2 ± 2%	41.3 ± 2%
SDT_5D_5	46.8 ± 2%	43.1 ± 2%	44.7 ± 2%	42.1 ± 2%

2.3.3. Crop Management

The observation of phenological dates and the measurement of yield components during the growth duration were conducted based on the Agrometeorological Observation Specification [38]. Ten plants per plot were selected randomly to measure plant height, above ground biomass and phenology at maturity in each growing period, and observed every 2 days during the maize warming period. At harvest, 10 plants in each plot were completely harvested to determine of yield components such as 100-grain weight, baldness to tip ratio, seed weight, spike thickness and spike length, determine grain yield, and dry weight of above ground biomass. Above ground biomass was determined by oven drying fresh samples at 72 °C for 48 h to a constant weight. Grain yield was determined after drying seeds in the sun to a constant grain weight.

2.3.4. Meteorological Data

Meteorological data including temperature, relative humidity, wind speed, and total radiation at 1-min intervals were obtained from the automatic weather station of the Gucheng Agrometeorological Experimental Station. The 30-year period from 1981 to 2010 was used as the climate state period for climate change analysis in the study area.

2.3.5. Statistical Analysis

The main interactive effects of high temperature, time, and drought, were determined using univariate ANOVA (analysis of variance) via the General Linear Models procedure. The biomass, yield components, ear characteristics, bald ratio, and plant height were determined from randomly collected samples from 10 complete plant stands in each plot. All data processing was conducted using the SPSS Statistics program (Version 22, IBM, Chicago, IL, USA).

3. Results

The mean monthly precipitation and temperature in 2016 and 2017 compared with the 30-year (1981–2010) mean records are shown in Figure 3. The annual precipitation was 491.3 mm in 2016 and 541.9 mm in 2017, whereas precipitation during the spring maize growing seasons (1 June to 30 September) was 392.6 mm in 2016 and 395.7 mm in 2017. The mean of 30-year annual precipitation was 496.1 mm, while the 30-year average precipitation during the spring maize growing seasons was 390.6 mm. Monthly rainfall reached 269.9 mm in July 2016 and 184.0 mm in August 2017. Although these rainfall values were higher than the 30-year July (153.8 mm) and August means (113.9 mm), 2016 and 2017 were considered normal years when compared with the 30-year mean annual record.

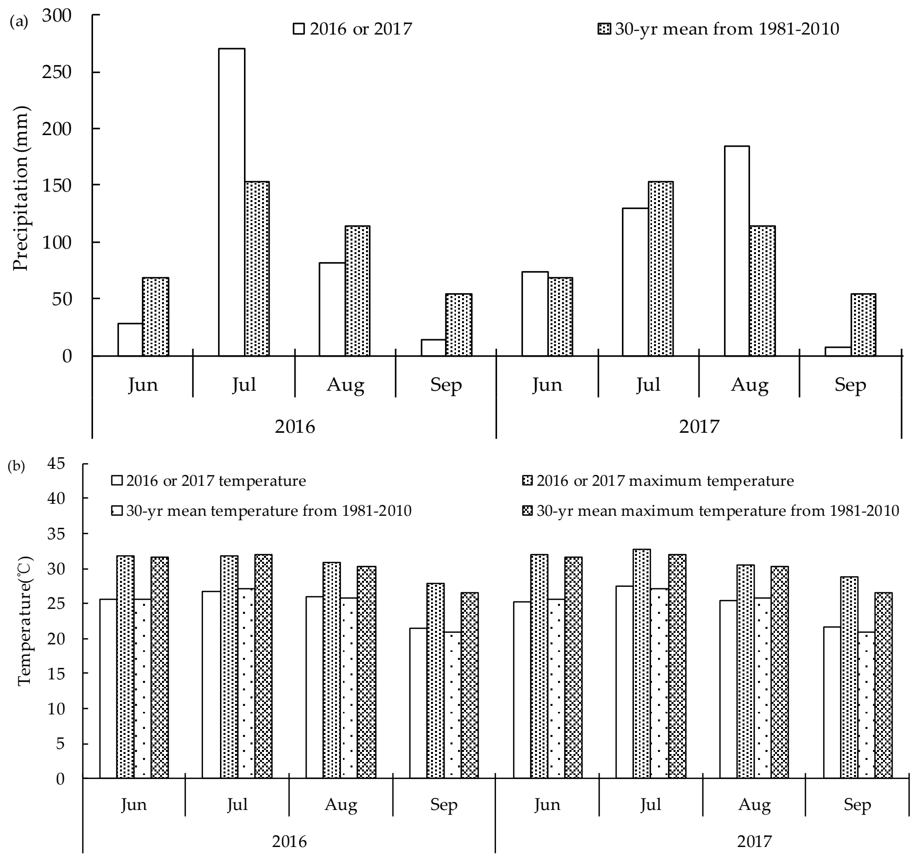

Figure 3. Mean monthly precipitations and temperature at the experiment site in 2016 and 2017 compared with the mean 30-year records (1981–2010) during the summer maize growing seasons, (**a**) Precipitation and (**b**) Temperature.

The annual maximum temperatures during the spring maize growing season were 30.5 °C in 2016 and 31.0 °C in 2017, respectively, with a 30-year average maximum temperature of 24.9 °C. The maximum temperatures in September were 27.8 °C in 2016 and 28.8 °C in 2017, respectively, with a 30-year average maximum temperature of 26.6 °C. The maximum temperature was higher than the 30-year average maximum temperature in September 2016 and 2017, but were considered normal when compared with the 30-year mean temperature during the spring maize growing seasons. The rainfall was considered normal, but August 2016 and 2017 had high temperatures during the spring maize growing seasons.

3.1. Impact on the Summer Maize Yields and Its Component Parts

The interaction effects of high temperature and drought on the yield composition of maize showed differences in the reproductive stage (Table 5). Drought reduced maize yields through negative effects on the yield components. Compared with NI, the significant decrease in grain yield and HI were 78.4% and 23.1%, respectively, for LD, while it was

94.7% and 66.9% for SD, and there was a significant decrease in ear length, ear thickness, 100-grain weight, and biological yield. However, the bald ratio was decreased.

Table 5. Effects of different treatments on maize yield and yield components.

	Ear Length (cm)	Ear Thickness (cm)	Bald Ratio (%)	Hundred-Grain Weight (G)	Grain Yield (g/m^2)	Harvest Index (%)	Biological Yield (g/m^2)
2016							
NI	12.78 a	4.53 a	1.11 c	32.39 a	1140.70 a	48.00 a	19,011.10 a
NIT_3D_5	12.93 a	4.58 a	1.55 ab	32.80 a	1141.07 a	48.77 a	19,552.10 ab
NIT_5D_7	12.61 a	4.50 a	1.65 a	30.27 b	1012.28 b	47.31 a	16,761.43 b
LD (LDT_5D_0)	6.89 b	3.38 b	1.67 bc	28.13 c	242.25 c	37.59 b	5156.10 c
LDT_3D_7	6.96 b	3.41 b	1.86 bc	28.46 d	247.56 c	41.62 b	5758.30 c
SD (SDT_3D_0)	6.26 b	2.77 c	1.82 bc	20.55 e	84.26 d	18.67 c	3609.95 c
SDT_5D_5	5.38 b	2.26 d	1.97 c	18.96 d	65.44 c	16.85 b	3518.77 c
2017							
NI	13.13 a	4.61 a	1.95 a	34.28 a	1177.14 a	55.76 a	16,888.65 a
NIT_3D_5	13.65 a	4.67 a	1.49 b	34.64 b	1258.64 a	56.16 a	17,928.48 a
NIT_5D_7	12.65 a	4.47 a	1.37 b	32.39 a	1140.70 a	55.65 a	16,310.08 a
LD (LDT_5D_0)	8.04 b	3.05 b	1.47 b	21.39 d	210.48 b	37.02 b	4548.35 bc
LDT_3D_7	8.18 b	3.23 b	1.20 bc	24.76 c	254.72 b	39.40 b	5448.22 b
SD (SDT_3D_0)	5.07 c	2.34 c	1.07 c	19.21 e	61.52 b	19.57 c	2515.15 cd
SDT_5D_5	4.94 c	2.06 d	1.27 bc	17.28 f	48.73 b	15.08 c	2484.57 d

Means within a column followed by the same letters are not significantly different at the 5% level (Tukey's-b test ANOVA).

The increase in temperature of 2.3 °C promoted the growth of maize, while the increase in temperature of 4.5 °C inhibited the growth of maize under sufficient soil water conditions. Compared with NI, the mean increase in grain yield and HI were 3.6% and 1.2%, respectively, for NIT_3D_5, however, the mean decrease in grain yield and HI were 7.2% and 1.1%, for NIT_5D_7, and there was a significant decrease in ear length, ear thickness, 100-grain weight, and biological yield.

The synergistic effect of high temperature and drought had a serious impact on the yield components of maize, resulting in serious yield reduction. Compared with NI, the significant decrease in grain yield and HI were 78.4% and 21.3%, respectively, for LDT_3D_7, while it was 95.1% and 47.1% for SDT_5D_5. Compared with LD, the increase in grain yield and HI were 11.6% and 8.6%, respectively, for LDT_3D_7, however, compared with SD, it significantly decreases by 21.6% and 16.3% for SDT_5D_5, and there was a significant decrease in ear length, ear thickness, 100-grain weight and biological yield.

The preferential temperature (temperature increase of 2.3 °C) increased the yield of summer maize under normal irrigation and mild drought, while high temperature (temperature increase of 4.5 °C) reduced maize yield under normal irrigation and severe drought. The synergistic effect of high temperature and drought significantly reduced maize yield compared with the individual effects of high temperature or drought. Drought mainly impacts grain yield by affecting dry matter accumulation during flowering or by directly affecting the function of pollen and ovule cells, which reduces grain setting ability. High temperatures reduce the supply of assimilates, which decreases the grain size and yield. High temperature and drought stress combined can reduce grain weight and yield by limiting the supply of assimilates or by directly affecting the grain synthesis process during the grain filling stage.

3.2. Impact on the Summer Maize Phenological Period

The phenophase of summer maize significantly differed between the treatments due to the interaction of high temperature and drought. Drought stress either delayed or advanced the phenological period of summer maize (Figure 4). Compared with NI, the mean delay of the vegetative stages was 5.5 days for LD, while it was 11 days for SD. However, the reproductive stages of maize were shortened due to the influence of drought. Compared with NI, the mean advance of the reproductive stages was 8 days for LD, while it was 15 days for SD in 2016. The mean advance of the reproductive stages was 2 days for LD and SD in 2017.

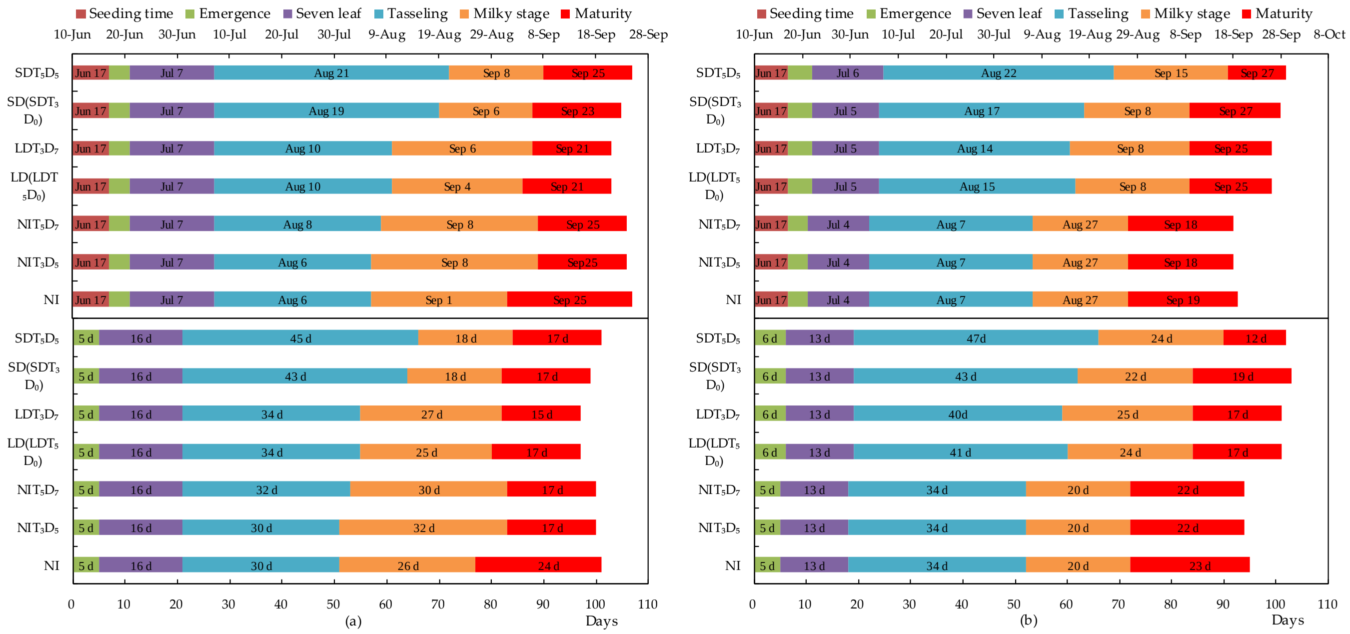

Figure 4. Maize phenology divided into sowing to beginning of seeding emergence, seven leaf stage, tasseling, milky stage, and end of maturity (upper half of each graph), and growing days (lower half part of each graph) for the growing seasons (**a**) 2016 and (**b**) 2017.

The reproductive stages of maize were shortened by increasing temperature under sufficient water. Compared with NI, the mean advance of the reproductive stages was 1 day for NIT_3D_5, while it was 2 days for NIT_5D_7 in 2016, and the mean advance of the reproductive stages was 1 day for LD and SD in 2017. The reproductive stages of maize were shortened under the synergistic effect of high temperature and drought. Compared with NI, the mean advance of the reproductive stages was 5 days for LDT_3D_7, while it was 11 days for SDT_5D_5.

Increasing temperature promoted the growth and development of summer maize and advanced plant phenophase under the same soil moisture during the reproductive growth stage. The growth period of SDT_5D_5 was the shortest, followed by LDT_3D_7, which were both under the synergistic effect of high temperature and drought; therefore, the synergistic effect of high temperature and drought promoted reproductive growth.

3.3. Impact on Summer Maize Grain Filling Rate

The grain filling process directly affects the formation of grains. The interaction of high temperature and drought had a significant effect on the grain filling rate of summer maize during the grain filling stage (Figure 5). The dry weight of the grain gradually increased with the progress of the grain filling process. The drought stress had restrained grain-filling rate and shortened grain-filling time. Compared with NI, the significant decrease of the grain-filling rate was 70.8% for LD, while it was 88.1% for SD.

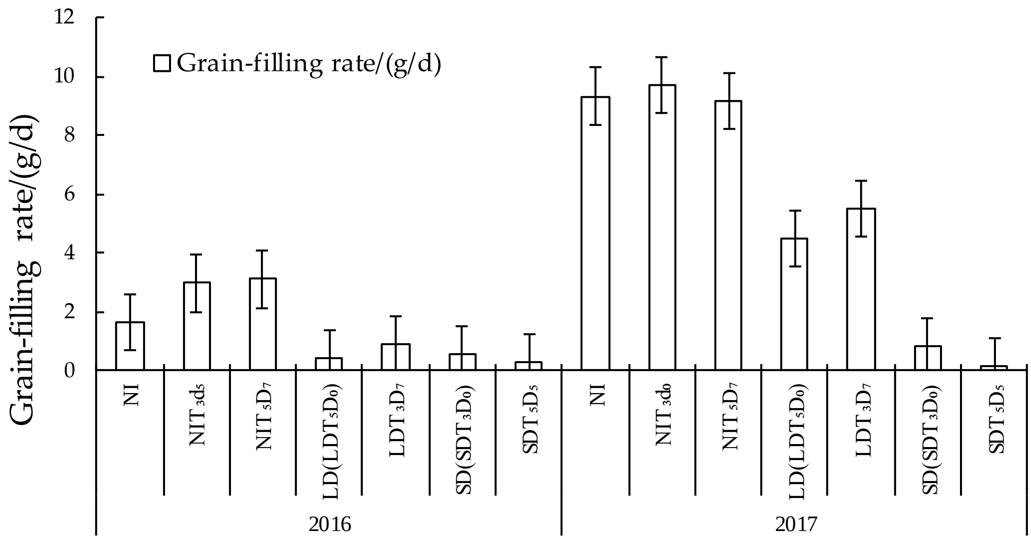

Figure 5. Response of grain filling rate to the interaction of high temperature and drought during the summer maize grout period.

The suitable temperature increased the grain filling rate of summer maize, while the high temperature reduced the grain filling rate under sufficient moisture. Compared with NI, the increase in the grain-filling rate was 6.6% for NIT_3D_5, but it decreased by 8.2% for NIT_5D_7. The grain-filling of summer maize had restrained, and the grain-filling rate significantly decreased under the synergistic effect of high temperature and drought. Compared with NI, the significant decrease in the grain-filling rate was 58.5% for LDT_3D_7, but it was 95.4% for SDT_5D_5. However, compared with LD, the mean increase in the grain-filling rate was 76.9% for LDT_3D_7, but the mean decrease in the grain-filling rate was 66.2% for SDT_5D_5, compared with SD.

The preferential temperature promoted grain filling under mild drought stress compared with LD, and high temperature inhibited grain filling under severe drought compared with SD. During the grain-filling stage, the preferential temperature (increase temperature of 2.3 °C) promoted the stalk-to-grain transport of carbohydrates, enhanced starch synthesis, and increased the yield of summer maize under NI and LD. The drought stress had restrained grain-filling rate and shortened grain-filling time, decreased transportation efficiency of photosynthetic product to harvest organ under drought stress conditions, which caused maize grain yield reduction. Moreover, the number of endosperm cells decreased, which affected starch synthesis during grain formation and reduced grain yield due to high temperature stress at the grain filling stage.

4. Discussion

The impacts of climate change on agricultural production will not be uniform across the world. Many studies have shown that climatic changes may affect the growth and yield of maize by applying the statistical model [12,39–41]. It was demonstrated that temperature increase reduces global yields of major crops (wheat, maize, and barley) by model estimates. In agreement, previous studies showed that high temperature and drought would lead to the decrease in maize and wheat yields on a large scale in the United States and Europe [42,43]. Drought stress significantly reduced the production of maize, wheat, and rice (three major food crops) due to high temperatures in Northeast China [44]. Mi, et al. [45] found that maize yields have the potential to increase in the northern part of Northeast China by combining regional climate models and WOFOST models. Liu, et al. [46] found that an increase in temperature of 2.5 °C reduced the yield of maize kernels during the growth period. Similarly, Zhang, et al. [47] noted a significant reduction in maize yield (from the bell stage to maturity) under a temperature increase of 3 °C using a growth box. Based on these studies, the effect of temperature increase on maize yield was inconsistent.

Drought is a major factor restricting increases in maize yield at regional to global scales. The effect of drought on maize yield formation gradually increased with drought aggravation in each growth period. However, compound stresses of high temperature and drought have a significantly higher impact on the inhibition of Gramineae plant growth and yield than the individual stresses [48]. Wang, et al. [37] found that the compound stresses of high temperature and drought had a significantly higher impact on maize yield than the individual stresses. Ding, et al. [49] also found that high temperature and drought stress during the maize flowering period reduced grain yield. High temperature stress significantly reduced the number of grains and grain weight during the filling stage, which resulted in a significant reduction of maize yield, especially when combined with drought stress [50–52]. When the temperature increased by 2 °C and the precipitation decreases by 20%, the crop yield is severely reduced [6]. The results of this study showed that a temperature increase of 2.3 °C increased the grain yield of maize in the grain filling stage, by about 4.5%, and a temperature increase of 4.5 °C significantly reduced the grain yield of maize under the sufficient water condition, by about 7.6%. The grain yield of maize was significantly increased by a temperature increase of 2.3 °C in the grain filling stage under mild drought. The grain yield of summer maize significantly decreased under high temperature and drought stress.

High temperature and drought stress reduced the transfer of assimilates to the grain, resulting in a decrease in the number of endosperm cells, limiting the supply of assimilates or directly affecting the synthesis process of the grain, thereby reducing grain weight. This directly affected the grain synthesis process and reduced grain weight. We found that summer maize growth can adapt to a climate warming of 2–2.5 °C during the grain-filling period in North China, but its yield significantly reduced under combined high temperature and drought conditions. This may be related to the differences in research methods, research parameters, planting layouts and climate scenario settings [11]. The yield fluctuation among different maize varieties is related to the local climate characteristics and planting layout. In this study, the influence of high temperature and drought on summer maize in the sub-humid area was studied. In the future, the interaction effects of high temperature and drought on maize yield in the arid and semi-arid area will be further studied. The grain yield of maize is closely related to the grain filling characteristics such as the rate and duration of filling [53]. The grain filling rate of summer maize was the highest under normal irrigation, followed by mild drought, and then severe drought. Under the sufficient water condition with adaptive temperature (3 °C), the grain filling rate of summer maize increased as temperature increased, but it decreased under high temperature (5 °C) condition. A previous study found that the grain-filling rate of summer maize was increased under adaptative temperature in mild drought conditions [54]. The grain filling rate of summer maize was significantly decreased under the combined stress of severe drought and high temperature. The results of this experiment were consistent with previous research, in which high temperature and drought stress shortened the grain filling period and reduced the filling rate and the grain yield [55–58]. High temperature and drought stress represent the major abiotic stress factors affecting maize filling rate during the grain filling period, so the interaction of high temperature and drought have significantly negative implications for grain filling [29]. Combined with this research, we found that an increase in temperature of 3 °C could increase the grain-filling rate, shorten the filling period, and enhance grain yield of summer maize under sufficient water and mild water stress in summer.

Extreme climate disasters have partially or completely damaged the stability of regional crop production. The present study suggests that extreme drought and high temperature events will be increasingly common, frequent, and severe, and considerable uncertainty persists about the extreme climate threat on agriculture production around the world. The purpose of this study is to explore the interaction effect of high temperature and drought on the grain filling period of summer maize. However, our preliminary results have some uncertainties that require further improvement, including trial representativeness (time and space), the role of adaptation measures, planting layout, tillage practices, variety renewal, and the variability of future climate scenarios [59]. The experiment in a single area can only reflect the local interactions of high temperature and drought on crops, and the experimental results cannot simply be extrapolated. It is necessary to conduct experimental studies and crop model simulations across more areas and over longer periods. This experiment is based on the premise that the current and future agricultural production status is consistent. In this study, only three factors and three levels of high temperature and drought experiments were adopted, and the response of summer maize to high temperature and drought has nonlinear characteristics. Future climate scenarios also have many uncertainties, and crop varieties and farming methods continually change. Therefore, it is necessary to conduct further long-term observations and simulation studies of multi-factor and multi-level high temperature and drought interactions during different growth stages to fully understand the influence rule on summer maize.

5. Conclusions

Drought significantly reduced the grain yield and yield components of summer maize, prolonged the reproductive growth stage, shortened the vegetative reproduction stage, and reduced the grain filling rate. Under the synergistic effect of high temperature and drought (NIT_3D_5 and LDT_3D_7), the summer maize grain yield, yield components, and bald tip ratio increased, and the grain filling rate was accelerated compared with that of NI and LD. Moreover, the grain yield, yield composition, and grain-filling rate of NIT_5D_7 and SDT_5D_5 decreased relative to that of NI and SD. Under both normal irrigation and drought stress, an increase in temperature shortened the phenological period and promoted the vegetative growth of summer maize during the grain-filling stage. The research results show that the summer maize growth was related to the degree of temperature increase and drought stress, and was not affected by the time of temperature increase.

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