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Research article

Maize grain filling characteristics in China: Response to meteorological factors

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ABSTRACT

To investigate the dynamic changes in dry matter accumulation in maize after anthesis, we established a logistic model to describe grain filling characteristics (GFC), and analyzed differences between spring and summer maize, and the influence of meteorological factors. The results showed that the logistic model accurately simulated the dynamic changes in grain growth. For spring maize, the fitted hundred-grain weight at maturity was closely related to the average grain filling rate until maturity, days of the active grain filling period, time of the maximum grain filling rate, and duration of the rapid increase in grain weight. For summer maize, it was closely related to the time of the maximum grain filling rate, days of active grain filling period, duration of gradual grain weight, and the rapidly increasing period. The filling characteristics of spring and summer maize differed because of the different meteorological conditions and biological characteristics. The grain filling duration of spring maize was longer than that of summer maize. The maximum grain filling rate of spring maize occurred later than that of summer maize. Temperature and precipitation were the main meteorological factors affecting the hundred-grain weight of spring maize, whereas temperature was the main factor affecting summer maize. The response of spring maize GFC to meteorological factors was more complex than that of summer maize. These results are important for the development of appropriate strategies for improving maize productivity in China.

1. Introduction

It is expected that by 2050, the world's major food production will need to double to meet the basic needs of mankind, and maize will contribute to 45 % of the global food demand [1]. Three components contribute to maize grain yield: the number of panicles per unit area, the grain number per ear, and the grain weight. These three components can be affected by many factors, such as maize variety, environment, and cultivation measures. The grain filling period is essential for maize yield. Quantitative analysis of the dynamic change characteristics of dry matter accumulation during the filling period and their impact factors is key to revealing the formation of maize yield.

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Research has shown that the grain weight of maize depends on the grain filling rate [2,3], whereas others believe that it depends on the filling duration [4]. Gao et al. [5] found that the grain filling duration and rate during the effective grain filling phase considerably contributed to the final performance parameter of the 100-kernel weight. However, these results were inconsistent. Grain filling characteristics (GFC) are considerably related to meteorological factors. High-temperature stress [6,7] and insufficient light [8] during the filling period considerably reduce the grain filling rate and yield. In field-grown maize production, temperatures above or equal to 33 °C during the filling period can reduce the number of grains per ear and inhibit the filling process [9,10]. Drought and waterlogging stress shorten the duration of maize grain filling and affect yield [11]. Liu et al. [12] reported that increased solar radiation accumulation during the GFP contributed to approximately 28.8 % of the increase in maize yield in China from 1985 to 2014. Therefore, it is crucial to quantitatively analyze the impact factors of grain weight and GFC in maize.

Available agroclimatic resources that can be absorbed and converted into dry matter can directly affect crop growth and yield under climate change [13]. Considering local weather and climate characteristics, scholars in different regions have studied the GFC of maize and its relationship with meteorological factors. Peng et al. [14] conducted relevant studies on maize in the plain area of Sichuan and pointed out that with delayed sowing dates, the growth period of maize decreased, and the grain yield and 100-kernel weight decreased considerably. The decreased yield was mainly attributed to the 100-kernel weight, and variations in the grain filling rate (G_{mean}) and kernel weight at the maximum grain filling rate (W_{max}) were the primary factors influencing the 100-kernel weight. G_{mean} and W_{max} were significantly influenced by effective accumulated temperature, daily average temperature, and precipitation following silking. Li et al. [15] studied GFC during the entire filling period based on interval sowing tests of three maize varieties in Harbin, and the results showed that the accumulated temperature, radiation, and saturated vapor pressure were significantly positively correlated with the filling rate. Increases in temperature and radiation in the early stage contributed to an increase in the filling rate for early-maturing varieties, whereas decreases in temperature and radiation in the later period substantially reduced the filling duration and rate for late-maturing varieties. Kernel weight was negatively correlated with precipitation after anthesis and positively correlated with radiation exposure. Zhou et al. [16] used field experiment data on maize and meteorological data from 2018 to 2020 at the Xifeng site to analyze the relationship between meteorological factors and GFC. The main meteorological factors affecting grain filling rate were mean temperature, maximum temperature, minimum temperature, daily temperature range, sunshine hours, air humidity, and precipitation. Temperature and sunshine had positive effects, whereas humidity and precipitation had negative effects. The sowing time of maize should be determined so that the rapid growth period of the hundred-grain weight coincides with the period of high temperature and little rain in Qingyang, thus achieving a stable and high yield. Dai et al. [17] selected two maize varieties in Heilongjiang and analyzed their grain filling and dehydration characteristics. Xianyu335 exhibited rapid grain filling velocity, physiologic dehydration, and higher yield contrasting with Zhengdan958 demonstrated a longer duration period of grain filling. Moreover, Zhengdan958 showed slower grain filling velocity during the early and middle stages of the filling period. The quick velocity of grain filling, natural dehydration, and high yield were observed in the later filling period of Zhengdan958. In arid and low-temperature areas, the grain filling duration cannot be used as an index to measure the filling quality, and the filling rate directly affects the grain filling process and yield. Zhou's study revealed that maize grain filling and duration were primarily influenced by temperature and radiation throughout the filling period. Furthermore, it was observed that longer filling duration corresponded to increased grain weight and yield [18]. Zheng [19] pointed out that there was a significant positive correlation between grain weight and filling rate as grain weight increased gradually, whereas there was a significant negative correlation between filling duration and grain weight. During the rapid period, the filling duration was positively correlated with grain weight, whereas the grain filling rate was negatively correlated. During the steady period, the degree of correlation between these two factors and grain weight was very low. The influence of meteorological conditions on dry matter accumulation in maize changes with growth. The same variety planted in different areas exhibited different filling characteristics. Chen et al. [20] found that the grain filling rate of Zhengdan958 in Jiangsu Province first increased and then decreased after pollination, reaching its maximum 20 days after pollination. Wu [21] pointed out that when Zhengdan958 was planted in the spring maize area of Jilin Province, the maximum grain filling rate appeared 24 days after pollination, and there was a high grain filling rate at 60 days after pollination. When Zhengdan958 was planted in Jilin Qiqihaer, the maximum grain filling rate occurred 31 days after pollination, and there was a high grain filling rate at 60 days after pollination. In conclusion, from south to north, the filling duration of Zhengdan958 was extended, and the time of the maximum filling rate was gradually delayed.

Many studies have been conducted to determine the effects of sowing dates [22–24] and meteorological factors on GFC and yield of maize. However, different varieties respond differently to the sowing dates and meteorological factors. There is a lack of quantitative comparative analysis of the GFC between spring and summer maize. Furthermore, previous studies analyzed the effect of meteorological factors, primarily light, temperature, and water, on GFC, but they lacked a comprehensive analysis of multiple factors. Thus, we incorporated soil temperature, an essential meteorological indicator, to provide a more thorough analysis of how GFC responds to meteorological factors. The research questions in this study were as follows: (1) What are the GFC of spring and summer maize in different maize-producing regions in China? (2) how do grain weight and GFC respond to complex meteorological factors? Overall, the objectives of this study were to (1) clarify specific GFC differences between spring and summer maize within a larger area, (2) identify the main GFC that affects the hundred-grain weight of spring and summer maize, (3) specify the key meteorological factors that influence the grain weight and GFC, and (4) provide a basis for increasing maize yield and avoiding risks.

2. Materials and methods

2.1. Experimental design

2.1.1. Study location and climate conditions

Based on collaborative experimental data on spring and summer maize planted in different regions from 2018 to 2020, this study analyzed the filling characteristics of maize and their relationship with meteorological factors. The study sites are shown in Fig. 1. The varieties and years are shown in the supplementary data (Table S1). There were 16 station years and 64 samples. Different sowing dates create different meteorological conditions for the growth and development of maize. The experiment consisted of four sowing dates based on the actual local field sowing dates. The first sowing date was 10 days earlier than the normal sowing date (T1). The second sowing date was considered normal (T2). The third sowing date was 10 days later (T3). The fourth sowing date was 20 days later (T4).

The potential maize planting areas in China are extensive, with major differences in climatic resources and cultivation systems. Different regions are suitable for different maize varieties. There are six maize-producing regions with different climate conditions [25–27] including the Northern spring maize region (I), Huang-Huai-Hai summer maize region (II), Northwest irrigated maize region (III), Southwest mountain maize region (IV), Southern hilly maize region (V), and Qinghai-Tibet maize region (VI). The study sites covered four maize-producing regions (Table S1), accounting for approximately 93 % of the total maize planting area in China.

The northern spring maize region has a cold, temperate, humid, and semi-humid climate. Winter temperatures are low. Accumulated temperatures of ≥10 °C range from 2000 to 3600 °C. The frost-free period lasts 130–170 days. The average temperature on the hottest day in summer is 20–25 °C. The annual precipitation ranges from 400 to 800 mm. High evaporation occurs in the spring, making the region prone to spring droughts. Single-cropping of spring maize is an important cropping system in this area.

The Huang-Huai-Hai summer maize region has a double-cropping system and belongs to a warm temperate semi-humid climate zone. The annual average temperature ranges from 10 to 14 °C, and the frost-free period lasts 170–240 days. Accumulated temperatures of ≥10 °C range from 3600 to 4700 °C. The annual precipitation ranges from 500 to 800 mm. Occasional spring droughts and summer floods also occur.

The irrigated maize region in northwest has a continental, arid climate with abundant sunshine and considerable diurnal temperature variations. However, with the limited annual precipitation of less than 200 mm, maize cultivation relies on irrigation. The main cropping system in this area is single-cropping of spring maize.

The southwest mountain maize region has good water and heat conditions but poor light conditions and belongs to a temperate, subtropical humid, and semi-humid climate zone. The average temperature from April to October is above 15 °C. The frost-free period lasts 240–330 days. The annual precipitation ranges from 800 to 1200 mm and is distributed relatively evenly. The main cropping system is double cropping, or five harvests over two years.

2.1.2. Study methods and observation items

Determination of filling rate: During the initial anthesis period of maize, 30 plants of the same size that flowered on the same day were selected for each treatment and dated. Samples were collected once every five days from the 10th day after anthesis until

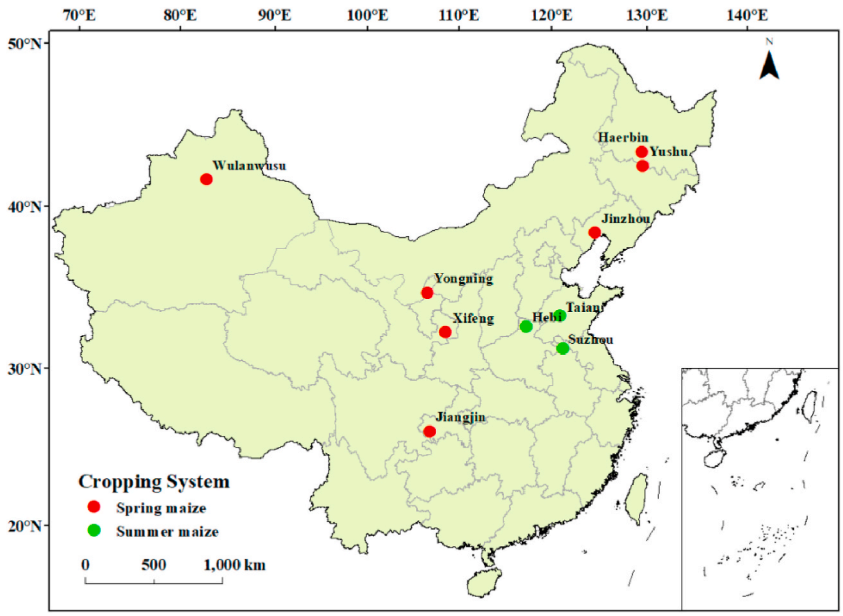

Fig. 1. Location of study sites in China.

maturity. Two ears were collected each time, the seeds were removed, the total number of grains was counted, and the seeds were placed in an aluminum box to determine the fresh and dry weights after drying. The dry weight of the grains per ear was calculated. The units (g ear^{-1}) were recorded to two decimal places.

Routine meteorological observations: The data included daily mean temperature, maximum temperature, minimum temperature, precipitation, sunshine hours, wind speed, relative humidity, maximum surface temperature, minimum surface temperature, and 5 cm, 10 cm, and 20 cm ground temperatures during the growth period, which were obtained directly from meteorological observation stations. The meteorological data corresponded to the time of the field trial.

2.2. Statistical methods and data processing

2.2.1. Logistic model

Many studies have shown that changes in crop biomass are consistent with logistic models. Therefore, logistic model (1) was used in this study to fit the grain filling process of maize, where Y is the filling quality, x is the number of days after anthesis, k is the theoretical maximum filling quality, and a and b are undetermined coefficients. The fitting process employed four-point and least-squares methods to determine the model parameters. Models were developed to describe the relationship between grain dry matter accumulation and days after anthesis for both spring and summer maize, accounting for various sowing dates and regions.

$$Y = k\left(1 + ae^{-bx}\right)^{-1} \tag{1}$$

2.2.2. Secondary parameters of the logistic model

By taking the first derivative of Equation (1), we can derive the grain filling rate from Equation (2), which can be used to calculate the active grain filling period and the average grain filling rate. The active grain filling period (T) was defined as the number of days for Y to reach 5 %–95 % of k. The average grain filling rate (V) was obtained by calculating the added mass of the grain during the active filling period and dividing by T.

$$Y' = kabe^{-bx}\left(1 + ae^{-bx}\right)^{-2} \tag{2}$$

By taking the second derivative of Equation (1), we can derive Equation (3). The maximum grain filling rate ($V_{\max}$) and the time of the maximum grain filling rate ($T_{\max}$) can be determined by setting $Y'' = 0$.

$$Y'' = -kab^2\frac{(1 - ae^{-bx})e^{-bx}}{(1 + ae^{-bx})^3} \tag{3}$$

By taking the third derivative of Equation (1), we can derive Equation (4). By setting $Y''' = 0$, the two inflection points (5,6) of the curve can be solved.

$$Y''' = -kab^3\frac{(4ae^{-bx} - a^2e^{-2bx} - 1)e^{-bx}}{(1 + ae^{-bx})^4} \tag{4}$$

$$x_1 = -\frac{\ln\left[\frac{2+\sqrt{3}}{a}\right]}{b} \tag{5}$$

$$x_2 = -\frac{\ln\left[\frac{2-\sqrt{3}}{a}\right]}{b} \tag{6}$$

Before x_1, the grain weight gradually increased. $x_1 \sim x_2$ showed a rapid increase in grain weight. The duration from x_2 to the time when Y reached 95 % of k was the period when the grain weight steadily increased. The duration and filling rate of each stage are denoted as t_1, t_2, t_3, V_1, V_2, and V_3. The solution process showed that the maximum grain filling rate, average grain filling rate, grain filling rate during the period of rapid grain weight increase, and grain filling rate during the period of steady grain weight increase were proportional. The duration of the rapid increase in grain weight was proportional to that of the steady increase.

2.2.3. Data processing

Data were analyzed and processed using Excel and SPSS software. The characteristic parameters of the logistic model were computed and plotted using Microsoft Excel and MATLAB.

3. Results

3.1. Characteristics of the logistic model describing the grain filling process of spring and summer maize

A logistic model was established based on the relationship between the number of days after anthesis and the filling quality of spring and summer maize. The coefficients and determination coefficients of the logistic model are provided in the supplementary data (Table S2). The coefficients of determination for each model ranged from 0.836 to 0.998. All the models reached significance, indicating that the filling process of spring and summer maize in each treatment was consistent with that of the logistic model.

The filling quality increased with filling time, and the rate of increase in the filling quality was fast in the early stage but slow in the late stage (Fig. 2a–p). Parameter *k* of the logistic model represents the maximum growth, that is, the theoretical maximum filling quality. The parameter *k* obtained for the same variety at different sowing dates differed, indicating that the theoretical maximum hundred-grain weight was affected by meteorological conditions. The *k* values of T1 and T2 in Harbin (2018) (Fig. 2a), Yushu (2018) (Fig. 2f), Xifeng (2020) (Fig. 2k), Suzhou (2019) (Fig. 2o), and Suzhou (2020) (Fig. 2p) were higher than those of T3 and T4, indicating that early or normal sowing may be more beneficial for high or stable yields. In contrast, the *k* values of T1 and T2 in Jiangjin (2018) (Fig. 2b), Jinzhou (2018) (Fig. 2c), Yongning (2018) (Fig. 2e), and Harbin (2019) (Fig. 2g) were lower than those of T3 and T4, indicating that timely late sowing may be more beneficial for high or stable yields.

The grain filling duration of spring (Fig. 3a) and summer maize (Fig. 3b) varied with different varieties and sowing dates. Overall, the grain filling duration of spring maize was longer than that of summer maize, with an average of 60.5 days for spring maize and 48.2 days for summer maize. According to the three consecutive years of observation at the Xifeng station, the grain filling duration in 2020 was the longest among the three years (2018–2020), but the hundred-grain weight was not the highest (lower than that in 2018), indicating that the yield was not only dependent on grain filling duration. The final grain weight depends not only on the grain filling duration but also on the meteorological conditions that determine the filling duration and filling rate.

3.2. Parameters of the logistic model and GFC of spring and summer maize

By comparing the hundred-grain weight at maturity fitted by the logistic model with the actual values of spring (Fig. 4a) and

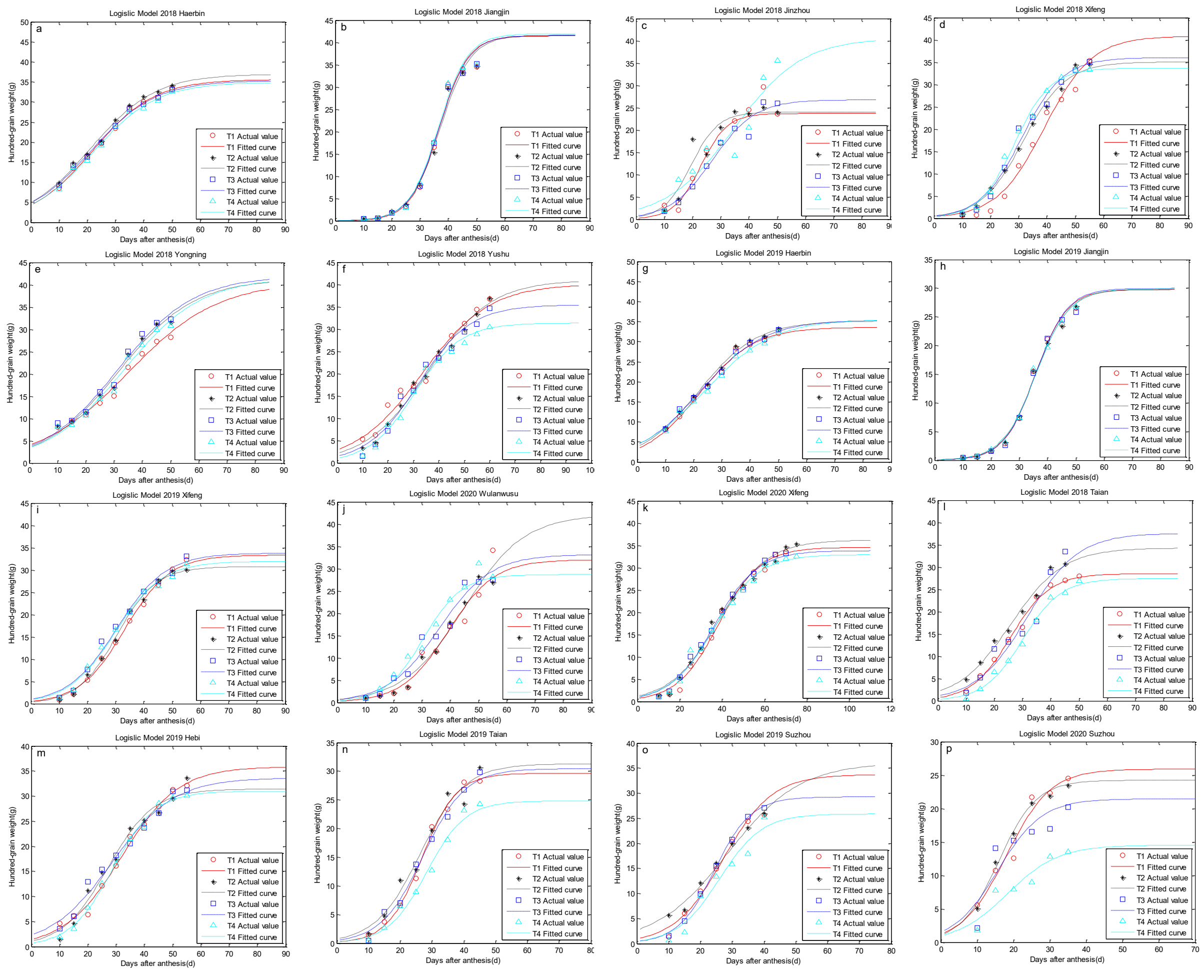

Fig. 2. Fitting results of the logistic model of maize. 2018 Haerbin (a), 2018 Jiangjin (b), 2018 Jinzhou (c), 2018 Xifeng (d), 2018 Yongning (e), 2018 Yushu (f), 2019 Haerbin (g), 2019 Jiangjin (h), 2019 Xifeng (i), 2020 Wulanwusu (j), 2020 Xifeng (k), 2018 Taian (l), 2019 Hebi (m), 2019 Taian (n), 2019 Suzhou (o), 2020 Suzhou (p).

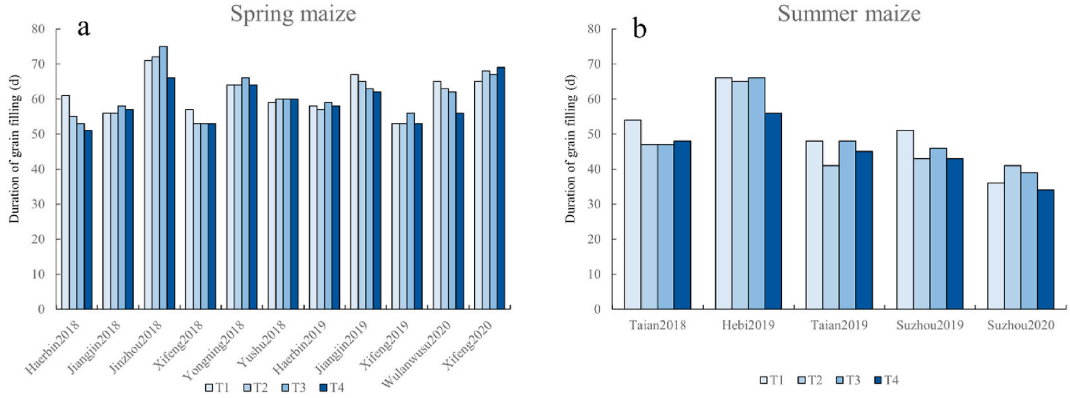

Fig. 3. Duration of grain filling in spring maize (a) and summer maize (b).

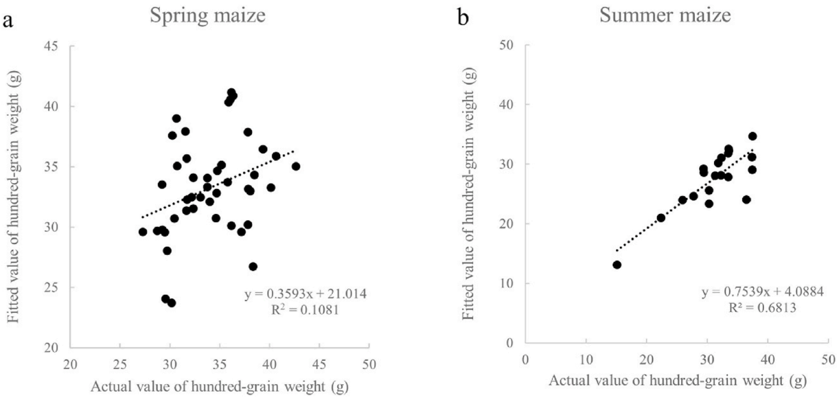

Fig. 4. Relationship between hundred-grain weight fitted by the logistic model and the actual values of spring maize (a) and summer maize (b).

summer maize (Fig. 4b), we found that the hundred-grain weight at maturity fitted by the logistic model showed a significant linear correlation with the actual values for spring and summer maize. The results showed that the model accurately simulated dynamic changes in grain development and final grain formation. The model performed better for summer maize ($R^2 = 0.68$) than for spring maize ($R^2 = 0.11$).

By analyzing the relationship between the hundred-grain weight fitted by the logistic model at maturity and the GFC of spring maize (Fig. 5a–h), we found that there was an extremely significant correlation between the fitted hundred-grain weight and the average grain filling rate until maturity ($P = 0.000$). There was a significant correlation between the fitted hundred-grain weight and duration of the active filling period ($P = 0.032$), time of the maximum grain filling rate ($P = 0.033$), and duration of rapidly increasing grain weight ($P = 0.033$). For summer maize (Fig. 5i-p), there was an extremely significant correlation between the fitted hundred-grain weight and the time of the maximum grain filling rate ($P = 0.001$). There was a significant correlation between the fitted hundred-grain weight and duration of the active filling period ($P = 0.021$), duration of the grain weight gradually increasing period ($P = 0.015$), and the duration of grain weight rapidly increasing period ($P = 0.021$).

Except for k and x_2, the variation coefficients of the spring maize parameters were larger than those of summer maize (Table 1), indicating that different meteorological conditions under different sowing dates may have a greater influence on spring maize than on summer maize. We compared the variation coefficients of V and T and found that the effect of the sowing date for spring maize on the average grain filling rate was greater than that of the active grain filling period, whereas the effect for summer maize was the opposite. We compared the variation coefficients of V_{max} and T_{max} and found that the effect of sowing date for spring maize on the maximum grain filling rate was greater than that of the time of the maximum grain filling rate, whereas the opposite was true for summer maize. For both spring and summer maize, the variation coefficient of x_1 was larger than that of x_2, suggesting that the effect of the sowing date on the time from the period of gradual grain weight to rapid grain weight increase was more significant than the transition from rapid grain weight increase to steady grain weight increase. For spring and summer maize, the variation coefficients of duration and grain filling rate of grain weight gradually increasing periods were larger than those of grain weight rapidly and steadily increasing periods. The results showed that the effect of the sowing date on the gradual increase in grain weight was greater than that in the other two periods.

The difference in the parameters of the logistic model between spring and summer maize was analyzed using an independent-samples T test (Table abbreviated). The results showed that parameters a, b, T, V, V_{max}, x_1, t_1, V_1, t_2, V_2, t_3, and V_3 were notably

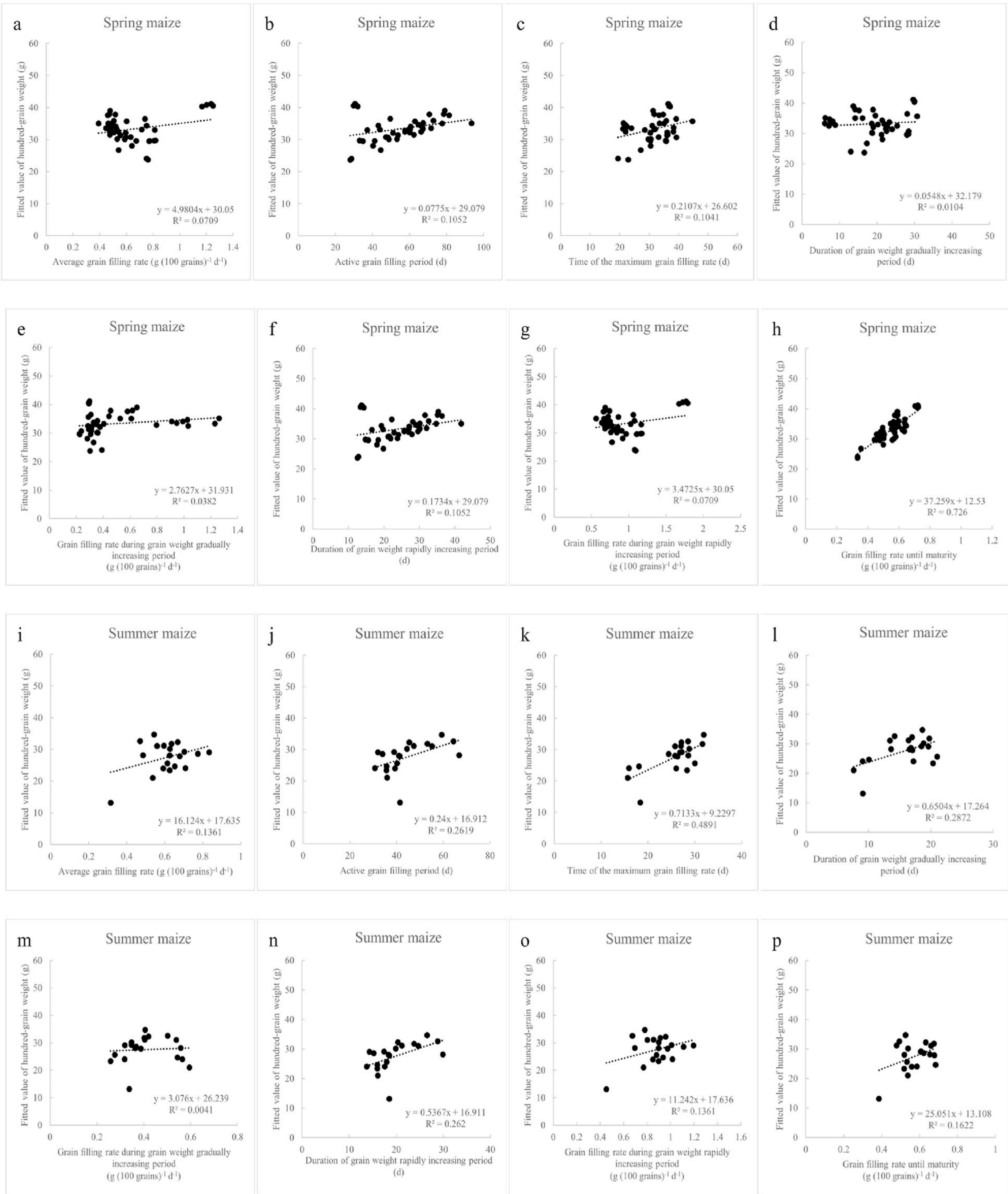

Fig. 5. Relationship between the hundred-grain weight fitted by the logistic model and the grain filling parameters of spring maize (a–h) and summer maize (i–p).

different between spring and summer maize ($P < 0.05$). Parameter a, duration of active grain filling period, x_1, duration and grain filling rate of grain weight gradually increasing period, duration of grain weight rapidly, and steadily increasing period of spring maize were considerably higher than those of the summer maize. Parameter b in spring maize was substantially lower than that in summer maize. The average grain filling rate, maximum grain filling rate, and grain filling rate during the rapidly and steadily increasing

Table 1
Grain filling characteristic parameters and variation coefficient of maize based on interval sowing tests.

Parameter	Spring maize				Summer maize			
	Variation amplitude	Mean	Standard deviation	CV%	Variation amplitude	Mean	Standard deviation	CV%
k	23.70 ~ 42.13	35.15	4.90	13.931	14.54 ~ 37.58	29.35	5.41	18.433
a	6.35 ~ 1395.56	179.63	331.78	184.704	12.42 ~ 137.93	43.08	32.96	76.508
b	0.06 ~ 0.21	0.12	0.04	34.038	0.09 ~ 0.19	0.14	0.03	20.724
V	0.39 ~ 1.25	0.64	0.21	33.472	0.32 ~ 0.83	0.61	0.11	17.944
T	27.97 ~ 93.5	53.77	16.82	31.276	30.78 ~ 66.85	44.15	10.24	23.194
V_{max}	0.64 ~ 2.04	1.05	0.35	33.471	0.52 ~ 1.36	1.00	0.18	17.944
T_{max}	19.45 ~ 44.75	31.54	6.15	19.516	15.68 ~ 31.94	25.63	4.71	18.374
x_1	6.07 ~ 30.67	19.51	7.50	38.424	7.62 ~ 21.04	15.75	3.96	25.123
x_2	25.88 ~ 58.83	43.56	6.92	15.878	22.84 ~ 45.21	35.50	6.26	17.630
t_1	6.07 ~ 30.67	19.51	7.50	38.424	7.62 ~ 21.04	15.75	3.96	25.123
V_1	0.22 ~ 1.26	0.48	0.28	59.599	0.26 ~ 0.59	0.41	0.10	24.125
t_2	12.51 ~ 41.82	24.05	7.52	31.276	13.77 ~ 29.90	19.75	4.58	23.194
V_2	0.56 ~ 1.79	0.92	0.31	33.471	0.45 ~ 1.20	0.88	0.16	17.944
t_3	7.73 ~ 25.84	14.86	4.65	31.277	8.51 ~ 18.47	12.20	2.83	23.194
V_3	0.25 ~ 0.81	0.42	0.14	33.472	0.20 ~ 0.54	0.40	0.07	17.945
V'	0.33 ~ 0.72	0.56	0.09	16.531	0.39 ~ 0.68	0.57	0.08	13.432

Notes: V: average grain filling rate (g (100 grains)$^{-1}$ d^{-1}); T: duration of active grain filling period (d); V_{max}: maximum grain filling rate (g (100 grains)$^{-1}$ d^{-1}); T_{max}: time of the maximum grain filling rate (d); x_1 and x_2: two inflection points of the model (d); t_1, V_1, t_2, V_2, t_3, V_3: duration (d) and grain filling rate (g (100 grains)$^{-1}$ d^{-1}) of grain weight gradually increasing period, grain weight rapidly increasing period, and grain weight steadily increasing period, respectively; V': grain filling rate until maturity (g (100 grains)$^{-1}$ d^{-1}).

periods of spring maize were considerably higher than those of summer maize. The maximum grain filling rate of spring maize occurred later than that of summer maize (31.54 days after anthesis on average for spring maize and 25.63 days after anthesis on average for summer maize). However, this difference was not statistically significant. The active grain filling period of spring maize was longer than that of summer maize, and the average filling rate (until Y reached 95 % of k) was higher than that of summer maize. Therefore, in theory, the final hundred-grain weight of spring maize should be higher than that of summer maize. The actual hundred-grain weight of spring maize at maturity was 34.05 (g) and that of summer maize was 31.07 (g) on average, with no significant difference. This was mainly because the grain filling rate until maturity was not significantly different between spring and summer

Table 2
Stepwise regression models of hundred-grain weight and grain filling characteristics respond to meteorological factors based on interval sowing tests.

	Parameter	Stepwise regression models	R^2	F	P
Spring maize	m	$m = -4.619 + 1.828R_4 + 1.653T_{5cm2} - 0.772T_{max5} + 0.428R_2 + 0.191T'_{max1}$	0.671	15.525	0.000
	k	$k = 6.355 + 3.598T_{5cm2} + 1.799R_4 - 2.817T_{20cm2}$	0.581	18.458	0.000
	V	$V = -0.679 + 0.059T_{min4} + 0.004RH_1 + 0.000A_4 + 0.074T_{max2} - 0.066T_{5cm2}$	0.878	54.823	0.000
	T	$T = 61.643 + 4.472T_{min4} + 18.689T_{5cm2} - 10.996T_{20cm2} - 8.054T_{20cm4} - 5.337T_{max2} + 1.081T'_{max4}$	0.890	49.862	0.000
	V_{max}	$V_{max} = -1.111 + 0.097T_{min4} + 0.006RH_1 - 0.001A_4 + 0.12T_{max2} - 0.108T_{5cm2}$	0.878	54.817	0.000
	T_{max}	$T_{max} = 34.402–2.212T'_{min3} + 0.388T'_{max1} + 1.274T_{min4}$	0.651	24.89	0.000
	t_1	$t_1 = 45.36 + 1.347T_{min4} - 1.65T'_{min3} - 0.286S_3 - 0.015A_1$	0.857	58.608	0.000
	V_1	$V_1 = -0.629 - 0.04T_{min4} + 0.01A_1 + 0.015S_3 + 0.043T'_{min5}$	0.800	39.073	0.000
	t_2	$t_2 = 27.572 + 2T_{min4} + 8.359T_{5cm2} - 4.918T_{20cm2} - 3.602T_{20cm4} - 2.387T_{max2} + 0.483T'_{max4}$	0.890	49.859	0.000
	V_2	$V_2 = -0.974 + 0.085T_{min4} + 0.006RH_1 - 0.001A_4 + 0.106T_{max2} - 0.094T_{5cm2}$	0.878	54.817	0.000
	t_3	$t_3 = 17.035 + 1.236T_{min4} + 5.165T_{5cm2} - 3.039T_{20cm2} - 2.226T_{20cm4} - 1.475T_{max2} + 0.299T'_{max4}$	0.890	49.878	0.000
	V_3	$V_3 = -0.441 + 0.038T_{min4} + 0.003RH_1 + 0.000A_4 + 0.048T_{max2} - 0.043T_{5cm2}$	0.878	54.834	0.000
Summer maize	m	$m = -46.442 + 0.014A_5 + 1.255T_{20cm1}$	0.733	23.303	0.000
	k	$k = -44.75 + 1.579T'_{max5}$	0.474	16.204	0.001
	V	$V = 2.044–0.096T_{20cm2} + 0.068T_{max5} - 0.014T_{max3}$	0.591	7.71	0.02
	T	$T = -120.043 + 5.469T_{20cm2}$	0.264	6.463	0.02
	V_{max}	$V_{max} = 3.344 - 0.157T_{20cm2} + 0.111T_{max5} - 0.023T_{max3}$	0.591	7.711	0.002
	T_{max}	$T_{max} = -90.376 + 3.331T_{max1} + 1.7R_5$	0.869	56.18	0.000
	t_1	$t_1 = 32.377–0.54RH_5 + 1.03T'_{min1}$	0.809	36.041	0.000
	V_1	$V_1 = -0.703 + 0.014RH_3$	0.442	14.255	0.001
	t_2	$t_2 = -53.691 + 2.446T_{20cm2}$	0.264	6.463	0.02
	V_2	$V_2 = 2.932 - 0.137T_{20cm2} + 0.097T_{max5} - 0.021T'_{max3}$	0.591	7.711	0.002
	t_3	$t_3 = -33.176 + 1.512T_{20cm2}$	0.264	4.646	0.02
	V_3	$V_3 = 1.326 - 0.062T_{20cm2} + 0.044T_{max5} - 0.009T'_{max3}$	0.591	7.709	0.002

Notes: A, T, T_{max}, T_{min}, R, S, RH, T'_{max}, T'_{min}, T_{5cm}, T_{10cm}, and T_{20cm} represents accumulated temperature (°C), average temperature (°C), average maximum temperature (°C), average minimum temperature (°C), average precipitation (mm), average sunshine hours (h), average relative humidity (%), average maximum surface temperature (°C), average minimum surface temperature (°C), average 5 cm ground temperature (°C), average 10 cm ground temperature (°C), average 20 cm ground temperature (°C), respectively. Corner marks 1–5 represents the sowing-jointing, jointing-tasseling, tasseling-milk, milk, and sowing-maturity stages, respectively. m was hundred-grain weight at maturity fitted by the logistic model (g).

maize, and that of summer maize was slightly higher than that of spring maize.

3.3. Effects of meteorological factors on hundred-grain weight and GFC of spring and summer maize

Stepwise regression models were developed for spring and summer maize, relating hundred-grain weight at maturity fitted by the logistic model and GFC to meteorological factors (Table 2). All models successfully passed the significance test. The hundred-grain weight at maturity (m) fitted by the logistic model for spring maize was mainly related to temperature and precipitation, whereas that of summer maize was mainly related to temperature. For spring maize, the higher the average precipitation from the milk stage to maturity, the average 5 cm ground temperature from jointing to tasseling, the average precipitation from jointing to tasseling, and the maximum surface temperature from seeding to jointing, the higher the fitted hundred-grain weight. Hundred-grain weight was inversely proportional to the maximum temperature during the entire growth period. The fitted hundred-grain weight of summer maize was proportional to the accumulated temperature during the entire growth period and the average 20 cm ground temperature from seeding to jointing. Overall, the response of spring maize GFC to meteorological factors was more complex than that of summer maize. The growth and development of spring maize have stringent environmental requirements.

4. Discussion

4.1. Basic conditions of the field trial

Liu et al. [28] proposed that only faster grain filling rates were detected for modern hybrids compared to older hybrids in another set of 14 Chinese single-cross hybrids. The difference in GFC is not only affected by intrinsic or environmental factors but also by other factors such as management practices and soil fertility [29–32]. In our study, the test field was flat without any obvious shelter. The soil type, tillage methods, maize variety, and soil fertility remained the same as those in the local fields. Spring maize was distinguished from summer maize across a wide range of regions for analysis. Except for k and x_2, the variation coefficients of the spring maize parameters were larger than those of the summer maize, indicating that different meteorological conditions at different sowing dates and in different regions may have a greater influence on spring maize than on summer maize. However, these aspects require further investigation.

4.2. Relationship between GFC of spring and summer maize and meteorological factors

Disaster risk reduction and climate change adaptation are essential for sustainable global development [33,34]. The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change stated that global surface temperatures in 2011–2020 were 1.09 °C above the temperatures in 1850–1900, of which the increase in land temperature was 1.59 °C and ocean warming was 0.88 °C [35]. Elements of the water cycle (e.g., precipitation, evaporation, runoff, and soil moisture content) have undergone major changes with climate change, which, in turn, has triggered the redistribution of water resources in time and space, resulting in droughts and extremely high temperatures on a global scale [36–38]. Many scholars have investigated how climatic factors (carbon dioxide concentration, temperature, and precipitation) affect the growth and development, variety maturity, suitable area, yield, and quality of maize [39–43]. Therefore, attention should be paid to the effects of agroclimatic resources and meteorological factors on maize.

According to the three consecutive years of observation at Xifeng station, the grain filling duration in 2020 was the longest among the three years (2018–2020), but the hundred-grain weight was not the highest (lower than that in 2018), indicating that the yield was not only dependent on grain filling duration. The final grain weight depends not only on the grain filling duration but also on the meteorological conditions that have the most fundamental influence on the filling duration and filling rate. Therefore, clarifying the response characteristics of grain filling and hundred-grain weight to meteorological factors is conducive to finding ways to mitigate the adverse effects of meteorological conditions. The results of our study demonstrate that adjusting the sowing date is a feasible method for achieving stable and high maize yield. Overall, the response of spring maize GFC to meteorological factors was more complex than that of summer maize. For spring maize, the hundred-grain weight at maturity fitted by the logistic model was primarily associated with temperature and precipitation, while that of summer maize was mainly related to temperature. We believe that we have generally identified a relationship between GFC and meteorological factors for spring and summer maize.

Differences in GFC between spring and summer maize may be due to differences in growth periods and biological characteristics. Spring maize is planted in the spring and has a longer growth period, whereas summer maize is planted in the summer and has a shorter growth period. Spring maize is susceptible to spring droughts, has a wider planting area than summer maize, and has relatively complex climate conditions. For example, water condition in the northwest irrigated maize region has a great influence on spring maize. This study revealed that the response of spring maize GFC to meteorological factors was more complex than that of summer maize. The results can be understood from the perspective of maize biological characteristics, distribution characteristics, and climate. The results can provide reference for planting strategies of spring and summer maize under the background of climate change.

4.3. Limitations

This study had some limitations. First, a large amount of experimental data is required to improve the applicability of the findings. The meteorological data corresponded to the time of the field trial. A total of 64 spring and summer maize samples were collected.

These data can be analyzed to reveal the preliminary relationship between meteorological factors and the GFC. In the future, more samples are required for the regression or validation of meteorological factors. Second, owing to the large number of selected meteorological factors and the division of the five growth stages, the importance ranking of influencing factors and how each factor affects the GFC remain to be analyzed. Third, the influence of abnormal climate cannot be ignored and requires further study. These limitations possess the potential to inspire future generations and more work needs to be done in the future.

5. Conclusions

The filling characteristic parameters of spring and summer maize differed because of the different meteorological conditions and biological characteristics. The grain filling duration of spring maize was longer than that of summer maize. The maximum grain filling rate of spring maize occurred later than that of the summer maize. The average grain filling rate until maturity had the greatest impact on the hundred-grain weight of spring maize, followed by the duration of the active filling period, the time of the maximum grain filling rate, and the duration of the rapid increase in grain weight. However, the time of the maximum grain filling rate was the most important factor for the hundred-grain weight of summer maize, followed by the duration of the active filling period, duration of the grain weight gradually increasing period, and duration of the grain weight rapidly increasing period. Temperature and precipitation were the main meteorological factors affecting the hundred-grain weight of spring maize, whereas temperature was the main factor affecting summer maize. Our results suggest that timely advancing or postponing the sowing time is beneficial for high and stable yields. This study provides a comparative analysis of the GFC between spring and summer maize. By incorporating the influential factors of soil temperature and considering the elements of light, temperature, and water, a more comprehensive analysis of the combined response of grain weight and GFC to meteorological factors can be achieved. The research findings can serve as a basis for precision planting, layout optimization, risk avoidance, and high maize yields. Additionally, they can serve as a reference for researchers in other regions or countries studying the maize GFC.

Data availability statement

Data will be made available on reasonable request.

CRediT authorship contribution statement

Rui Li: Writing – original draft, Software, Investigation, Conceptualization. **Cuiying Zhang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jianping Guo:** Writing – review & editing, Project administration, Data curation. **Yichen Liu:** Software, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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