Regional growth model for summer maize based on a logistic model: Case study in China

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Abstract: The growing degree days (GDD) is an important factor for crop growth because it affects dry matter formation and crop yield. In this study, the universal logistic models were established employing GDD and the relative GDD (RGDD) as the main parameters to characterize summer maize growth indices such as plant height (*H*), leaf area index (LAI), and dry matter accumulation (DMA). The relationships were analyzed between the growth indices, harvest index (HI), water consumption, and yield in maize. By considering China as an example, the results showed that the logistic model performed well at simulating the changes in the summer maize growth indices in different regions and the universal model parameters were within specific ranges. Furthermore, the logistic model with RGDD as the independent variable was more suitable for modeling summer maize growth in large areas than GDD. The relationship between the maximum LAI and HI was described by a quadratic polynomial function. HI was optimal (0.53) when the maximum LAI was about 5.13. The maximum LAI, maximum *H*, and maximum DMA could be described by a quadratic polynomial function of water consumption during the growing season. The summer maize yield could be predicted with a binary quadratic equation using the maximum GDD and water consumption. This study confirmed that a logistic model can be used to establish a universal growth model for summer maize in large areas. Reasonable ranges of parameters were recommended for the logistic model, as well as the reasonable water consumption and each growth index value for summer maize. These results will be helpful for predicting the growth and yield of summer maize.

Keywords: summer maize, water consumption, logistic model, growing degree days, growth index of crop
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1 Introduction

The global climate has changed substantially in recent years and it severely threatens food security[1-6]. In addition, rapid population growth and economic development have increased the demand for food crop production[7]. Maize is one of the main grain crops grown throughout the world[8-11]. In 2017, the area where maize was harvested worldwide comprised 1.97×10^8 hm^2, which was second only to wheat[12]. The total area planted with maize in China accounted for 17.7% of that throughout the world and its production was second only to that of the United States, which accounted for 18.6% of global maize production[12]. Summer maize production in China is mainly distributed in the North China Plain and northeast, and areas with low production are located in southern China[13-15]. However, the maize yield has not been high in recent years and it has even decreased in some areas[16], while there are large differences between regions[17,18]. Thus, a reasonable and efficient method is needed to evaluate the growth characteristics of maize in different regions and to provide a scientific basis for yield improvements.

de Wit[19] proposed the first model for describing crop growth. Crop models are now effective tools for assessing crop productivity and they can predict the potential impacts of climate change on future productivity, as well as play important roles in the management and regulation of crop growth and development[20-22]. Several programs have been developed for simulating maize growth processes, such as GERES-Maize[23], EPIC[24], DSSAT-Maize[25], APSIM-Maize[26], CropSyst[27], and Hybrid-Maize[28]. These models play important roles in studies of maize growth under different climates, irrigation and fertilization practices, field management systems, and yield prediction[29]. Different parameters are required for the models according to the different climates, soils, and other conditions in various regions, and thus it is necessary to estimate the parameters when using these models. Regional models must also be constructed to describe the growth and yield of crops in different regions[30].

Crop indices such as the plant height (*H*), leaf area index (LAI), and dry matter accumulation (DMA) can reflect the growth conditions, and they are also correlated with the final yield to some extent[31,32]. These three indices are used in most crop growth models and the yield can be predicted by establishing an analogous model based on the crop growth indices. Logistic model was originally proposed by ecologists to describe the laws of biological population growth and was widely applied in predicting dry matter accumulation, plant height growth, and leaf area expansion due to

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its high accuracy. For example, Khan et al.[33] established a series of logistic equations to simulate the cotton biomass under different sowing dates and plant densities conditions. Ma et al.[34] and Wang et al.[35] severally used the logistic model to simulate dry matter accumulation of spring wheat and winter wheat in different irrigation regimes. Liu et al.[36] and Wang et al.[37] developed a universal model for predicting the growth indexes of winter wheat and cotton based on the logistic model, respectively. Wang et al.[38] established growth functions for H and LAI in summer maize using logistic and modified logistic equations, and obtained good fitting precision. Fang et al.[39] employed the Richards equation[40] to predict the dry 100-grain weight by using the post-flowering time as an independent variable. However, these models were used to study changes in the crop growth indices over time in specific regions. Models are often affected by meteorological conditions, so their use in a wide range of conditions is not recommended[41]. Simulations of different regions or models are difficult to compare due to the inconsistency of the parameters[42], so the accuracy of simulations is not easy to determine[21].

The growing degree days (GDD) was first proposed as an ecosystem index in the 1730s for studying diurnal variations in temperature and their impact on different plant growth stages as the basis for the development of crops adapted to future climates[43]. GDD is the sum of the effective temperature accumulated during the growth of a crop and it can represent the comprehensive influence of temperature on all aspects of growth in order to analyze the suitable thermal conditions for the crop[44]. The GDD required for an entire growing season is relatively stable for a crop within a geographic region, and it can be used to express the length of the growing season when the temperature and other environmental factors are suitable[45-47]. Lin et al.[48] established a logistic model of the increases in the foliar area based on GDD for various maize varieties. The growth stage represented by GDD has used an independent variable in the model and simulations indicated that the variable trends were similar for the LAI and growth period. It was more practical to use the change in the LAI over time as an independent variable but maize LAI data were only available for Shandong and Hebei provinces, so the model could not be applied to a large area. Wang et al.[49] established a modified logistic model of the increase in the maize LAI based on data from Yucheng and Shenyang, but the suitability of this model for universal application still needs to be demonstrated. Zhang et al.[50] observed that the model proposed by Lin et al.[48] neglects the effects of excessively high or low temperatures on maize growth when calculating GDD and the summer maize indices must be measured during the silking period, thereby imposing a specific time limitation. Thus, the normalized GDD was employed as a variable by calculating the GDD using the mean temperature, and a modified form of the logistic equation proposed by Wang[51] was used to fit the relationship between the relative LAI (RLAI) and growth period for different maize varieties. The dynamic changes in the LAI were simulated and analyzed, and the simulated and measured values were highly correlated. Therefore, the growth characteristics of summer maize under different treatments in the same area can be described using a normalized model, but the relationships between the growth characteristics of summer maize in different areas still require further analysis.

GDD can be used to identify suitable sowing dates, growth periods, and the physiological characteristics of crops under specific conditions[52,53], before predicting the yield and harvest index (HI) for different sowing dates[54]. HI is also known as an economic coefficient and it was first proposed by Ni[55] and Donald[56]. HI is the ratio of the economic to biological yield at harvest, which represents the ability of crop products to be converted into economic products. The HI for summer maize has been correlated with parameters such as canopy coverage and plant dry matter[57,58], but the quantitative relationship has rarely been studied between LAI and HI for summer maize. LAI and GDD can be correlated to represent the crop biomass amount to some extent, so HI and LAI must have an inherent relationship[59-63].

In this study, data for summer maize were collected from many sources to determine the quantitative relationship between HI and maximum LAI. Growth indices (H, LAI, and DMA) for summer maize in China (mainly northern China) were modeled with logistic and modified logistic equations using GDD or RGDD as an independent variable. The relationships between growth indices, GDD, RGDD, water consumption, and yield in various areas were analyzed in order to identify common changes in the areas, as well as to determine the appropriate GDD and water consumption for the entire growing season and to improve yield prediction accuracy.

This study provides a theoretical basis and appropriate technical parameters for analyzing the growth characteristics of summer maize at different spatial scales and for establishing a universal model of summer maize growth.

2 Data sources and research methods

2.1 Data sources

Growth characteristics data for summer maize were obtained from 136 publications from 1987 to 2018 available via the China National Knowledge Infrastructure, which covered 54 regions in China. Meteorological data (mainly temperature and rainfall data) were collected from the National Meteorological Information Center of China. The following principles were applied for collecting the crop-growth data: (1) data were obtained directly from the text or figures using GetData Graph Digitizer; (2) all data selected were representative, excluding data obtained from rarely used agricultural practices; and (3) more than three sets of data samples were chosen for most regions, and 1-2 sets were obtained for only a few areas.

The main areas for growing summer maize were in northern China, the middle and lower reaches of the Yellow River, northeastern China, and the Xinjiang Uygur Autonomous Region. The soil texture was mainly loam in the maize-growing areas. Different varieties of summer maize were sown in various regions in the selected studies from late April to mid-June and harvested from late August to early October. Nitrogenous fertilizer (urea) was used as the base fertilizer in the experimental fields. Potassium fertilizers (KCl, K_2SO_4, and K_2O) and phosphorus fertilizers (P_2O_5, $NH_4H_2PO_4$, and superphosphate) were applied after the seedling, 12-leaf, or filling stage, depending on the nutrient conditions in the soil. The numbers of samples and data sources are listed in Tables 1-7.

2.2 Analysis methods

2.2.1 Relationships between relative growth indices, GDD, and RGDD

Publications describing the growth characteristics of summer maize were analyzed to collect data regarding the variations in H, LAI, and aboveground DMA. The variations in H with GDD and RGDD were analyzed using 162 data sets (Table 1); the variations in LAI with GDD and RGDD were analyzed using 824 data sets (Table 2); the variations in DMA with GDD and RGDD were analyzed using 302 data sets (Table 3).

GDD and RGDD were calculated for the summer maize growing season in various regions using data obtained from the China Meteorological Data Network (http://data.cma.cn/). The relationships between the indices representing maize growth characteristics, GDD, and RGDD were analyzed, and suitable growth models for different regions were integrated.

Table 1 Sample sizes and data sources for plant height in the study regions

Province	City (district)	Sample size	References	Province	City (district)	Sample size	References
Henan	Jiaozuo	6	[64, 65]	Hebei	Handan	4	[80]
Henan	Kaifeng	8	[66, 67]	Hebei	Xinji	16	[81]
Henan	Zhengzhou	3	[68]	Beijing	Haidian	3	[82]
Henan	Zhumadian	5	[69, 70]	Beijing	Daxing	4	[83]
Henan	Xinxiang	24	[71-74]	Beijing	Tongzhou	9	[84]
Shandong	Zaozhuang	7	[75]	Jilin	Jilin	6	[85]
Shandong	Jining	2	[76]	Anhui	Tianchang	20	[86-88]
Shandong	Dezhou	5	[77]	Tianjin	Wuqing	7	[89]
Shandong	Laizhou	6	[78]	Heilongjiang	Jiamusi	5	[90]
Shaanxi	Yangling	20	[79]	Shaanxi	Xianyang	1	[91]

Table 2 Sample sizes and data sources for the leaf area index in the study regions

Province	City (district)	Sample size	References	Province	City (district)	Sample size	References
Henan	Huangfan	4	[92]	Jilin	Changchun	3	[150]
Henan	Yuzhou	4	[93]	Jilin	Huadian	5	[151]
Henan	Jiaozuo	18	[65, 94-97]	Jilin	Jilin	6	[85]
Henan	Shangqiu	23	[98-100]	Jilin	Changchun	8	[152, 153]
Henan	Kaifeng	11	[66, 67, 101]	Shaanxi	Weinan	2	[154]
Henan	Anyang	15	[102, 103]	Shaanxi	Yangling	33	[79, 155, 156]
Henan	Luoyang	16	[104-107]	Shaanxi	Xianyang	1	[91]
Henan	Zhengzhou	40	[68, 108-111]	Gansu	Wuwei	7	[157]
Henan	Hebi	26	[112-115]	Jiangsu	Yangzhou	12	[158]
Henan	Zhumadian	25	[69, 70, 116-120]	Jiangsu	Nanjing	5	[159]
Henan	Xinxiang	38	[71-74, 110, 121, 122]	Hebei	Baoding	29	[132, 160, 161]
Henan	Pingdingshan	8	[123, 124]	Hebei	Cangzhou	58	[162-168]
Henan	Xuchang	3	[110, 125]	Hebei	Handan	4	[80]
Heilongjiang	Jiamusi	5	[90]	Hebei	Langfang	6	[169, 170]
Heilongjiang	Mishan	11	[126, 127]	Hebei	Xinji	16	[81]
Shandong	Zaozhuang	7	[75]	Hebei	Shijiazhuang	27	[171-173]
Shandong	Tai'an	83	[128-133]	Tianjin	Wuqing	7	[89]
Shandong	Linyi	32	[134, 135]	Anhui	Fuyang	6	[174]
Shandong	Jining	41	[136-140]	Anhui	Tianchang	20	[86-88]
Shandong	Qingdao	14	[141]	Beijing	Beijing	1	[175]
Shandong	Dezhou	10	[77, 142]	Beijing	Haidian	46	[176-182]
Shandong	Laizhou	6	[78]	Beijing	Daxing	4	[83]
Shandong	Yantai	12	[143-145]	Beijing	Tongzhou	9	[84]
Shandong	Zibo	5	[146]	Nei Monggol	Ordos	30	[183]
Liaoning	Shenyang	17	[147, 148]	Liaoning	Haicheng	5	[149]
Liaoning	Haicheng	5	[149]				

Table 3 Sample sizes and data sources for dry matter accumulation in the study regions

Province	City (district)	Sample size	References	Province	City (district)	Sample size	References
Jilin	Changchun	7	[150, 152]	Henan	Yuzhou	4	[93]
Jilin	Jilin	6	[85]	Henan	Jiaozuo	12	[64, 95-97]
Jilin	Lishu	3	[184]	Henan	Shangqiu	8	[99]
Beijing	Haidian	27	[82, 177, 180, 181]	Henan	Anyang	12	[102]
Shaanxi	Yangling	23	[79, 156]	Henan	Luoyang	8	[104, 107]
Shandong	Tai'an	26	[132, 134]	Henan	Zhengzhou	5	[187]
Shandong	Linyi	20	[132, 137]	Henan	Zhumadian	4	[118]
Shandong	Jining	19	[76, 139, 140]	Hebei	Cangzhou	8	[168]
Shandong	Dezhou	5	[142]	Hebei	Langfang	31	[169, 170, 188, 189]
Shandong	Yantai	7	[144, 145]	Hebei	Shijiazhuang	12	[172, 173]
Shandong	Zibo	5	[146]	Nei Monggol	Ordos	30	[183]
Sichuan	Ya'an	18	[185, 186]				

Each crop has upper and lower biological temperature limits, above and below which the crop ceases to grow[190]. The upper and lower biological temperature limits for summer maize are 40°C and 7°C, respectively[191]. GDD is the difference between the daily average temperature and the minimum temperature required for crop activity:

$$\mathrm{GDD}=\sum(T_{\mathrm{avg}}-T_{\mathrm{base}}) \tag{1}$$

where, T_{avg} is the mean daily temperature, °C; T_{base} is the minimum temperature required for crop activity, °C. McMaster and Wilhelm[46] proposed the following method for calculating T_{avg}:

$$\begin{cases} T_{\mathrm{avg}}=\dfrac{(T_x+T_n)}{2} \\ T_{\mathrm{avg}}=T_{\mathrm{base}}, \quad \text{if } T_{\mathrm{avg}}\le T_{\mathrm{base}} \\ T_{\mathrm{avg}}=T_{\mathrm{upper}}, \quad \text{if } T_{\mathrm{avg}}\ge T_{\mathrm{upper}} \end{cases} \tag{2}$$

where, T_{upper} is the maximum temperature tolerated for crop activity, °C; T_x is the daily maximum temperature, °C; T_n is the daily minimum temperature, °C.

Representative data (e.g., different planting years and areas) were selected to describe the relationships between the growth indices and GDD, and to analyze the characteristic changes based on a large amount of data. Curves were then drawn between each relative growth index and GDD in different regions. The following logistic models (Equations (3) and (4)) and modified logistic model (Equation (5)) were used to analyze the variations in H, DMA, and LAI for the different regions:

$$\mathrm{RH}=\frac{H}{H_{\max}}=\frac{1}{1+e^{a_0+a_1x}} \tag{3}$$

$$\mathrm{RDMA}=\frac{\mathrm{DMA}}{\mathrm{DMA}_{\max}}=\frac{1}{1+e^{b_0+b_1x}} \tag{4}$$

$$\mathrm{RLAI}=\frac{\mathrm{LAI}}{\mathrm{LAI}_{\max}}=\frac{1}{1+e^{c_0+c_1x+c_2x^2}} \tag{5}$$

where, a_0, a_1, b_0, b_1, c_0, c_1, and c_2 are empirical parameters; $H_{\max}$, $\mathrm{DMA}_{\max}$, and $\mathrm{LAI}_{\max}$ are the theoretical maxima of H (cm), DMA (kg/hm^2) and LAI, respectively; x is an independent variable that can be GDD or RGDD; RGDD is calculated by dividing GDD for each growth stage by the maximum GDD in the whole growth period.

The models for H were verified using experimental data from Kaifeng[66], Tianchang[88], Jining[76], Yangling[79], and Jilin[85]. The model for the increase in LAI was verified using experimental data from Qingdao[141], Cangzhou[167], Yangling[155], Yangzhou[158], and Shenyang[148]. The model for the increase in DMA was verified using experimental data from Langfang[169], Tai'an[134], Anyang[102], Ya'an[185], and Changchun[150]. The soils in the verification data sets were mainly loam and clay loam. The climate in the region where the data were verified was mostly a monsoon climate.

2.2.2 Relationships between $H_{\max}$, $\mathrm{LAI}_{\max}$, $\mathrm{DMA}_{\max}$, and water consumption

227 data sets were collected from 29 regions to establish the relationship between $H_{\max}$ and water consumption (Table 4), 65 data sets from nine regions to establish the relationship between $\mathrm{LAI}_{\max}$ and total water consumption (Table 5), and 204 data sets from 29 regions to establish the relationship between $\mathrm{DMA}_{\max}$ and water consumption (Table 6). The range of water consumption was divided into eight intervals: 100-200, 200-300, 300-400, 400-500, 500-600, 700-800, 900-1000, and 1000-1100 mm. The average water consumption and the corresponding $\mathrm{LAI}_{\max}$ were calculated, and the relationship between them was determined. The relationships between $H_{\max}$, $\mathrm{DMA}_{\max}$, and water consumption were established using the same method.

Table 4 Sample sizes and data sources for the maximum leaf area index, water consumption, and yield in the study regions

Province	City (district)	Sample size	References
Henan	Jiaozuo	2	[95]
Henan	Kaifeng	4	[101, 115]
Henan	Xinxiang	25	[71, 73, 192, 193]
Henan	Xuchang	2	[125]
Hebei	Cangzhou	8	[168]
Anhui	Tianchang	6	[88]
Beijing	Daxing	4	[181]
Beijing	Tongzhou	9	[84]
Shaanxi	Yangling	5	[194]

Table 5 Sample sizes and data sources for the maximum plant height and water consumption in the study regions

Province	City (district)	Sample size	References
Henan	Kaifeng	7	[101, 125]
Henan	Xinxiang	25	[71, 73, 192, 193]
Henan	Jiaozuo	10	[96, 195]
Shandong	Jining	18	[76]
Shandong	Zaozhuang	7	[75]
Shandong	Dezhou	10	[77, 142]
Shandong	Tai'an	16	[130]
Shandong	Yantai	5	[143]
Shaanxi	Yangling	26	[79, 91, 194]
Anhui	Tianchang	13	[87, 88]
Beijing	Tongzhou	9	[84]
Beijing	Haidian	32	[177, 181, 182]
Hebei	Cangzhou	20	[163, 168]
Hebei	Huanghua	4	[196]
Beijing	Daxing	4	[83]
Shanxi	Linfen	4	[197]
Tianjin	Wuqing	7	[89]

Table 6 Sample sizes and data sources for the maximum dry matter accumulation and water consumption in the study regions

Province	City (district)	Sample size	References
Shandong	Yantai	5	[143]
Shandong	Dezhou	10	[77, 142]
Shandong	Jining	17	[139, 140]
Shandong	Zibo	10	[146]
Shandong	Linyi	32	[134, 135]
Shandong	Tai'an	15	[129, 198]
Henan	Shangqiu	8	[99]
Henan	Anyang	12	[102]
Henan	Xuchang	2	[125]
Henan	Luoyang	5	[74, 104]
Henan	Jiaozuo	10	[95, 97]
Henan	Zhumadian	11	[70, 118, 119]
Hebei	Cangzhou	8	[166]
Hebei	Shijiazhuang	8	[172]
Anhui	Tianchang	7	[87]
Beijing	Haidian	17	[177, 179, 180]
Shaanxi	Yangling	20	[79]
Jilin	Changchun	7	[152, 199]

2.2.3 Relationship between $\mathrm{LAI}_{\max}$ and HI

HI is the ratio of economic to biological yield at harvest and it represents the ability of crops to convert photosynthetic and assimilative products into economic products. In our study, the relationship between LAI and HI was determined based on 211 data sets for 24 regions (Table 7). The range of $\mathrm{LAI}_{\max}$ was divided into seven intervals: 3-4, 4-5, 5-5.5, 5.5-6, 6-7, 7-8 and 8-9, based on the LAI_{max} characteristics, and the quantitative relationship between LAI_{max} and its corresponding HI was determined using the averages for each interval. The relationship was determined between LAI_{max} and HI.

Table 7 Sample sizes and data sources for the maximum leaf area index and the harvest index in the study regions

Province	City (district)	Sample size	References
Henan	Yuzhou	8	[93]
Henan	Jiaozuo	3	[66, 95]
Henan	Shangqiu	8	[99]
Henan	Kaifeng	3	[101]
Henan	Anyang	15	[102, 103]
Henan	Luoyang	11	[106, 107]
Henan	Hebi	4	[114]
Henan	Zhumadian	6	[69, 116]
Henan	Xinxiang	11	[110, 121]
Henan	Xuchang	3	[110, 125]
Henan	Zhengzhou	1	[110]
Hebei	Baoding	13	[160]
Hebei	Cangzhou	8	[166]
Hebei	Langfang	3	[169]
Hebei	Shijiazhuang	11	[117, 172]
Jilin	Changchun	7	[152, 199]
Beijing	Haidian	21	[177, 180, 181]
Shandong	Tai'an	20	[132, 196]
Shandong	Linyi	32	[134, 135]
Shandong	Jining	2	[76]
Shandong	Dezhou	5	[142]
Shandong	Yantai	5	[143]
Shandong	Jinan	5	[200]
Xinjiang	Wujiaqu	6	[201]

2.2.4 Water-heat coupling relationship for summer maize yield

In total, 46 data sets were collected for the yield, GDD_{max}, and water consumption (Table 4), where 36 datasets were used to analyze the water-heat coupling relationship for the summer maize yield by using a binary quadratic equation, and 10 sets were used to verify the established equations.

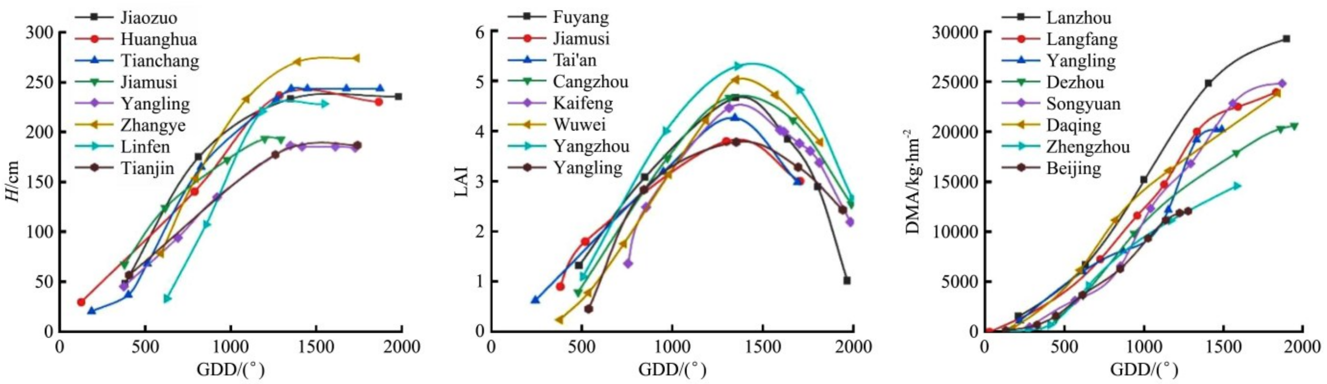
2.3 Statistical and error analyses

All statistical analyses were conducted using SPSS 22.0 (IBM Corp., Chicago, IL, USA). Errors were analyzed using the coefficient of determination (R^2), root mean square error ($RMSE$), and relative error (Re) to test the correlations.

3 Results

3.1 Relationships between relative growth indices and GDD

Figure 1 shows the curves obtained for the three summer maize growth indices as GDD increased at different sites. H and DMA increased slowly with GDD in the early stages, rapidly in the intermediate stages, and the increases gradually stopped in the later stages, where the increases in H and DMA were similar at all sites. The regular variation in LAI with GDD was obvious, and the increasing and decreasing trends in LAI were consistent with each other. The growth rates of H and LAI were slow when GDD<500°C. When GDD ranged between 500°C and 1000°C, both H and LAI increased rapidly. The growth rates of H and LAI decreased when GDD was between 1000°C and 1300°C. H and LAI reached their maximum values when GDD was about 1400°C. LAI gradually decreased when GDD>1400°C. The growth of DMA was slow when GDD<700°C. Dry matter accumulated rapidly when GDD was between 1000°C and 1400°C. The DMA rate decreased when GDD>1400°C, before peaking in the maturation stage when GDD increased to about 2000°C.



a. H and GDD b. LAI and GDD c. DMA and GDD

Figure 1 Relationships between plant height (H), leaf area index (LAI), dry matter accumulation (DMA), growing degree days (GDD) in the study regions

H_{max} differed greatly among the test sites (Figure 1a), as well as LAI_{max} (Figure 1b) and DMA_{max} (Figure 1c). The relative plant height (RH), relative leaf area index (RLAI), and relative dry matter accumulation (RDMA) were used to identify the characteristic variations among the sites, and the relationships were determined between RH, RLAI, RDMA, and GDD. The highest and lowest data points were used to fit the upper and lower envelope curves (Figure 2). RH, RLAI, and RDMA were fitted with GDD using Equations (6)-(8).

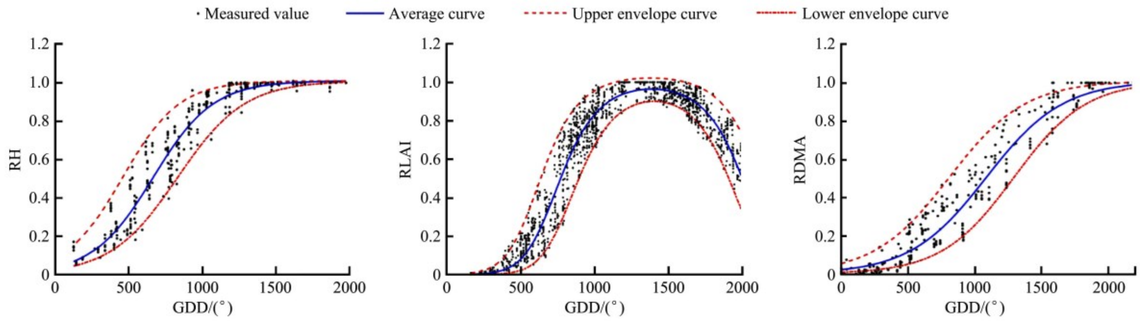
$$\mathrm{RH}=\frac{1}{1+e^{3.266-4.9\times10^{-3}\mathrm{GDD}}} \tag{6}$$

$$\mathrm{RLAI}=\frac{1}{1+e^{9.135-0.016\mathrm{GDD}+5.8\times10^{-6}\mathrm{GDD}^2}} \tag{7}$$

$$\mathrm{RDMA}=\frac{1}{1+e^{3.803-3.5\times10^{-3}\mathrm{GDD}}} \tag{8}$$

Table 8 lists the fitted parameters for the upper and lower envelopes around RH, RLAI, and RDMA. The upper and lower envelopes fitted well with the highest and lowest data points, and all of the R^2 values were 0.99. Experimental data from five other regions were used to verify the model (Figure 3) and the average curves simulated the measured values well. Comprehensive comparisons indicated that the average curves provided the best simulations for RH, RLAI, and RDMA.

The average curves were used to describe the relationships between RH, RLAI, RDMA, and GDD. The first-order derivative functions of Equations (6) and (8) were used to calculate the slopes



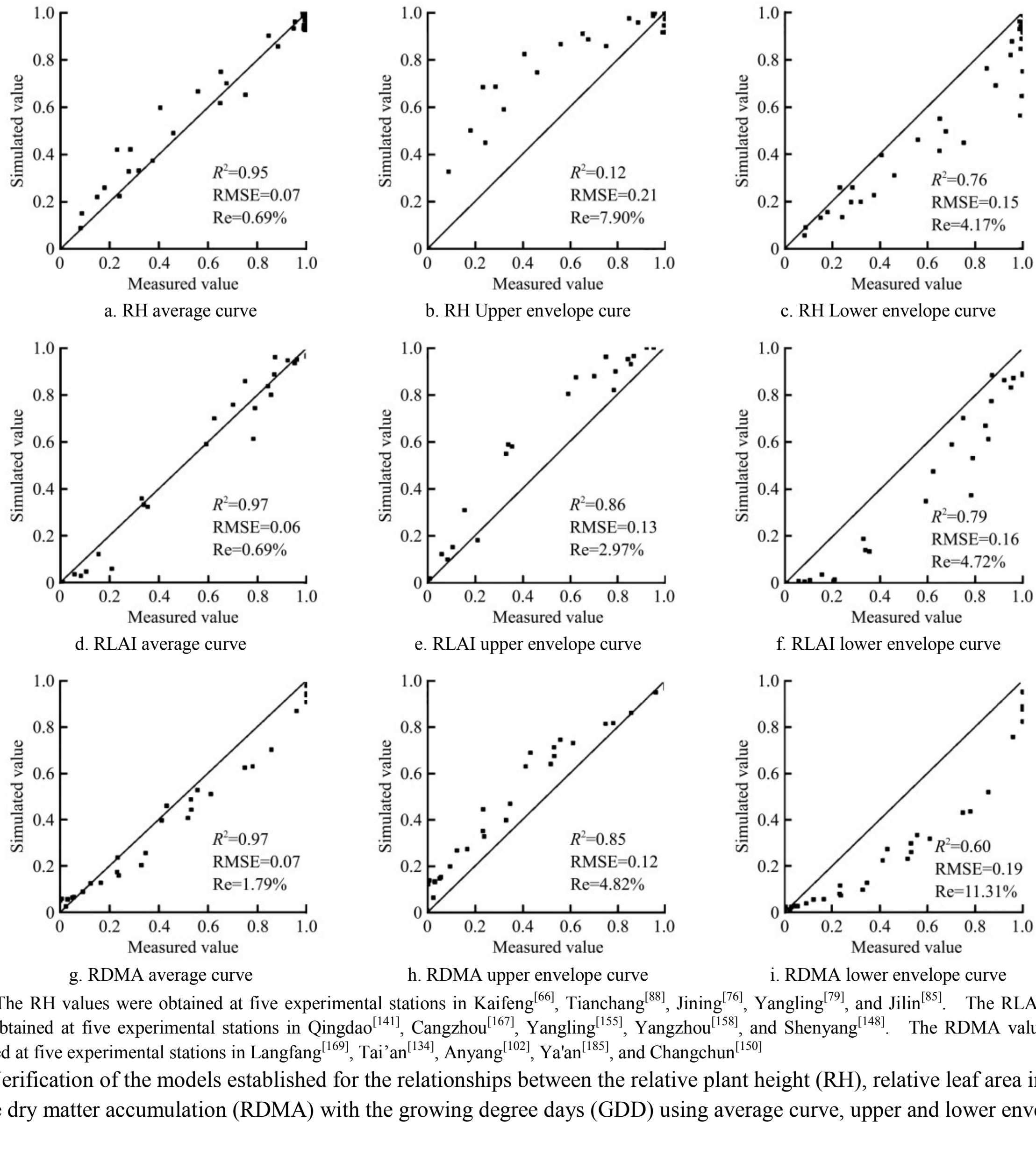
a. RH and GDD b. RLAI and GDD c. RDMA and GDD

Note: The upper and lower envelopes were fitted with the highest and lowest data points, respectively.

Figure 2 Relationships between relative plant height (RH), relative leaf area index (RLAI), relative dry matter accumulation (RDMA), and growing degree days (GDD), and comparisons between the measured values and fitted curves

Table 8 Logistic model parameters determined for the average curve and the upper and lower envelope curves for the relationships between the relative plant height (RH), relative leaf area index (RLAI), and relative dry matter accumulation (RDMA) with the growing degree days (GDD)

Type	RH-GDD			RLAI-GDD				RDMA-GDD		
	a_0	a_1	R^2	c_0	c_1	c_2	R^2	b_0	b_1	R^2
Average curve	3.266	-4.9×10^{-3}	0.95	9.135	–0.016	5.8×10^{-6}	0.87	3.803	-3.5×10^{-3}	0.95
Upper envelope curve	2.338	-5.2×10^{-3}	0.99	7.167	–0.014	5.2×10^{-6}	0.99	2.860	-3.5×10^{-3}	0.99
Lower envelope curve	3.666	-4.3×10^{-3}	0.99	11.600	–0.019	6.7×10^{-6}	0.99	4.784	-3.7×10^{-3}	0.99



a. RH average curve b. RH Upper envelope cure c. RH Lower envelope curve

d. RLAI average curve e. RLAI upper envelope curve f. RLAI lower envelope curve

g. RDMA average curve h. RDMA upper envelope curve i. RDMA lower envelope curve

Note: The RH values were obtained at five experimental stations in Kaifeng[66], Tianchang[88], Jining[76], Yangling[79], and Jilin[85]. The RLAI values were obtained at five experimental stations in Qingdao[141], Cangzhou[167], Yangling[155], Yangzhou[158], and Shenyang[148]. The RDMA values were obtained at five experimental stations in Langfang[169], Tai'an[134], Anyang[102], Ya'an[185], and Changchun[150]

Figure 3 Verification of the models established for the relationships between the relative plant height (RH), relative leaf area index (RLAI), and relative dry matter accumulation (RDMA) with the growing degree days (GDD) using average curve, upper and lower envelope curves of the curves for RH and RDMA. The slopes of the growth curves for RH were 0.0004, 0.0010, 0.0012, 0.0006, and 0.00004 for GDDs of 200°C, 500°C, 700°C, 1000°C, and 1600°C, respectively, which represent different summer maize growing stages. Thus, the slopes of the curves increased initially and then decreased. The rate of increase in *H* was slow and then fast, before finally becoming slow again. The slopes of the curves for RDMA were 0.00014, 0.00036, 0.00059, 0.00087, and 0.00065 for GDDs of 200°C, 500°C, 700°C, 1000°C, and 1600°C, respectively. The increase in the rate of DMA was largest when GDD was about 1000°C, which is consistent with the results in Figure 2.

Let:

$$\frac{d^2\text{RH}}{d\text{GDD}^2}=\frac{d^2\text{RDMA}}{d\text{GDD}^2}=0$$

The inflection point of the curve for RH occurred when GDD = $-a_0/a_1$ = 700°C. The rate of increase in H gradually increased when GDD<700°C but gradually decreased when GDD>700°C. GDD = $-b_0/b_1$ = 1000°C, which is the inflection point of the curve for RDMA. Thus, the rate of increase in DMA gradually increased when GDD<1000°C and gradually decreased when GDD>1000°C.

The quantitative relationship between *H* and LAI was obtained by combining Equations (6) and (7), as follows.

$$\text{RLAI}=\frac{1}{1+e^{0.240\ln^2\left(\frac{1}{\text{RH}}-1\right)+1.713\ln\left(\frac{1}{\text{RH}}-1\right)+1.002}} \tag{9}$$

The corresponding LAI based on *H* measured in a growing season was calculated using Equation (9). The first-order derivation of Equation (9) was below zero, thereby indicating that $\frac{\text{LAI}}{\text{LAI}_{\max}}$ increased when $\frac{H}{H_{\max}}$ increased. LAI was closer to its maximum when *H* was near its maximum. According to the variations in LAI and *H* with GDD, LAI and *H* both increased when GDD<1400°C, and they were positively correlated. Both LAI and the rate of increase in *H* gradually decreased when GDD>1400°C.

3.2 Relationships between relative growth indices and RGDD

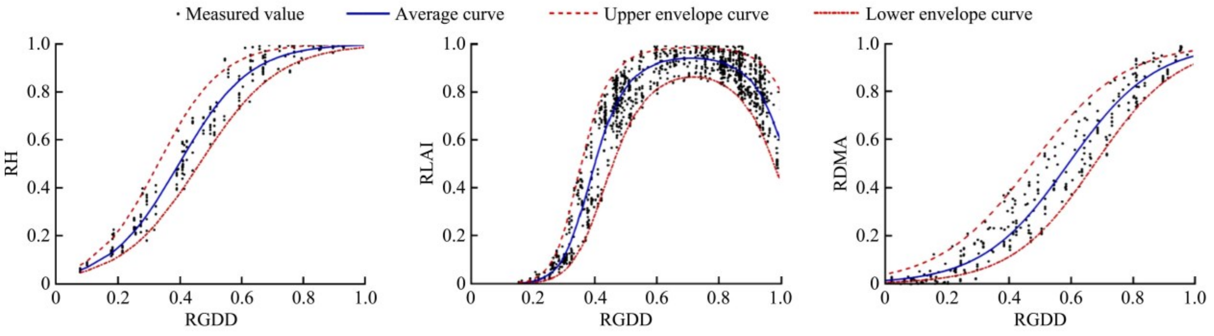
The relationships between the relative growth indices for summer maize and RGDD are plotted in Figure 4. The variations in each index were the same as those shown in Figure 2. The increases in RH and RDMA were both characterized by changes from small to large values and then to small values, whereas RLAI increased initially and then decreased. Both RH and RLAI increased slowly when RGDD<0.3. Both RH and RLAI increased rapidly when RGDD ranged between 0.3 and 0.5. The increases in RH and RLAI were smaller than before when RGDD ranged between 0.5 and 0.6. The values of RH and RLAI gradually stabilized when RGDD>0.6. RLAI declined rapidly when RGDD> 0.8. The increase in RDMA was greater when RGDD was between 0.4 and 0.7 compared with that when RGDD<0.4. The increase in RDMA was small and RDMA gradually stabilized when RGDD> 0.7. The changes in the indices shown in Figure 4 were fitted using the following logistic models.

$$\text{RH}=\frac{1}{1+e^{3.192-8.013\text{RGDD}}} \tag{10}$$

$$\text{RLAI}=\frac{1}{1+e^{7.385-28.150RGDD+20.320\text{RGDD}^2}} \tag{11}$$

$$\text{RDMA}=\frac{1}{1+e^{4.143-7.028\text{RGDD}}} \tag{12}$$

The logistic model parameters for the three relative growth indices fitted with RGDD are listed in Table 9. The upper and lower envelopes fitted well with the outermost data points, and all of the R^2 values were 0.99. The average curves for the three growth indices all fitted well with the measured point values, and R^2>0.85. Figure 5 shows the validation results obtained with Equations (10)-(12). The average curves fitted each of the indices best (R^2>0.95 and *Re*<1%). Therefore, the average curve can be used as the fitted curve between each growth index and RGDD.



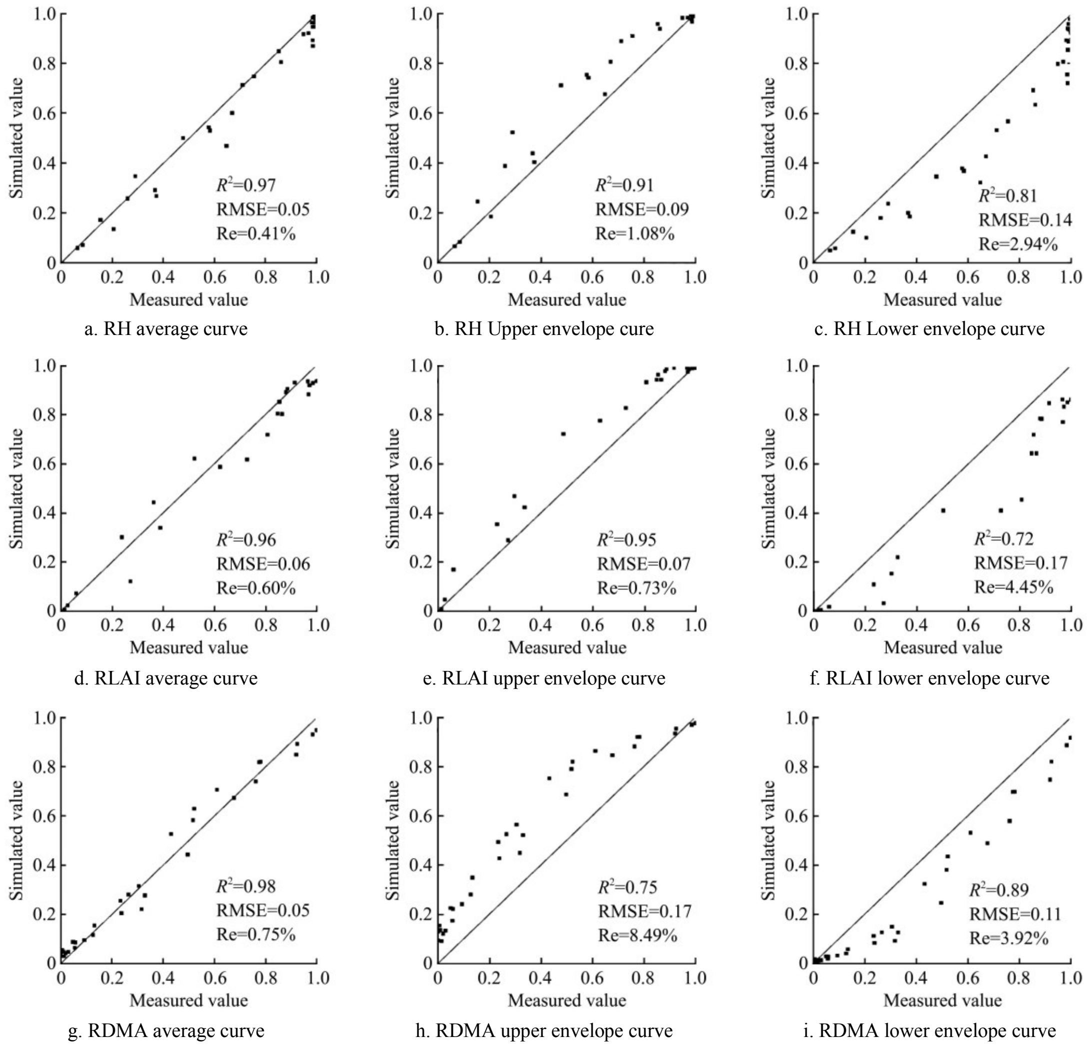
a. RH and RGDD b. RLAI and RGDD c. RDMA and RGDD

Note: The upper and lower envelopes were fitted with the highest and lowest data points, respectively.

Figure 4 Relationships between relative plant height (RH), relative leaf area index (RLAI), relative dry matter accumulation (RDMA), and relative growing degree days (RGDD), and comparisons of the measured values and fitted curves

Table 9 Logistic model parameters for the average curve and upper and lower envelope curves for the relationships between the relative plant height (RH), relative leaf area index (RLAI), and relative dry matter accumulation (RDMA) with the relative growing degree days (RGDD)

Type	RH-RGDD			RLAI-RGDD				RDMA-RGDD		
	a_0	a_1	R^2	c_0	c_1	c_2	R^2	b_0	b_1	R^2
Average curve	3.192	−8.013	0.96	7.385	−28.150	20.320	0.89	4.143	−7.028	0.95
Upper envelope curve	3.150	−10.520	0.99	7.102	−29.037	20.860	0.99	3.159	−6.675	0.99
Lower envelope curve	3.333	−6.175	0.99	7.661	−27.260	19.210	0.99	5.017	−7.412	0.99



Note: The RH values were obtained at five experimental stations in Kaifeng[66], Tianchang[88], Jining[76], Yangling[79], and Jilin[85]. The RLAI values were obtained at five experimental stations in Qingdao[141], Cangzhou[167], Yangling[155], Yangzhou[158], and Shenyang[148]. The RDMA values were obtained at five experimental stations in Langfang[169], Tai'an[134], Anyang[102], Ya'an[185], and Changchun[150]

Figure 5 Verification of the models established between the relative plant height (RH), relative leaf area index (RLAI), and relative dry matter accumulation (RDMA) with the relative growing degree days (RGDD) using average curve, upper and lower envelope curves

Let:

$$\frac{\mathrm{d}^2\mathrm{RH}}{\mathrm{dRGDD}^2}=\frac{\mathrm{d}^2\mathrm{RDMA}}{\mathrm{dRGDD}^2}=0$$

The inflection point of the curve for RH occurred when RGDD $= -a_0/a_1 = 0.40$. H increased gradually when RGDD<0.40 and decreased gradually when RGDD>0.40. RGDD $= -b_0/b_1 = 0.59$, which is the inflection point of the curve for RDMA. Thus, DMA increased gradually when RGDD<0.59 and decreased gradually when RGDD>0.59. Let:

$$\frac{\mathrm{dRLAI}}{\mathrm{dRGDD}}=0$$

RLAI reached the maximum when RGDD=0.70, which is consistent with the characteristics shown in Figure 4.

3.3 Relationships between H_{max}, LAI$_{max}$, DMA$_{max}$, and water consumption

The relationships obtained between the water consumption and H_{max}, LAI$_{max}$, and DMA$_{max}$ are shown in Figure 6. These three growth indices tended to increase initially and then decrease as water consumption increased. The relationships between H_{max}, LAI$_{max}$, DMA$_{max}$, and water consumption could be described by the following three quadratic polynomial functions:

$$\begin{cases} H_{\max} = -3.4\times10^{-4}W^2 + 0.4275W + 115.6629 \\ \mathrm{LAI}_{\max} = -8\times10^{-6}W^2 + 0.01W + 1.9818 \\ \mathrm{DMA}_{\max} = -0.0154W^2 + 19.1935W + 1.4744\times10^4 \end{cases} \quad (13)$$

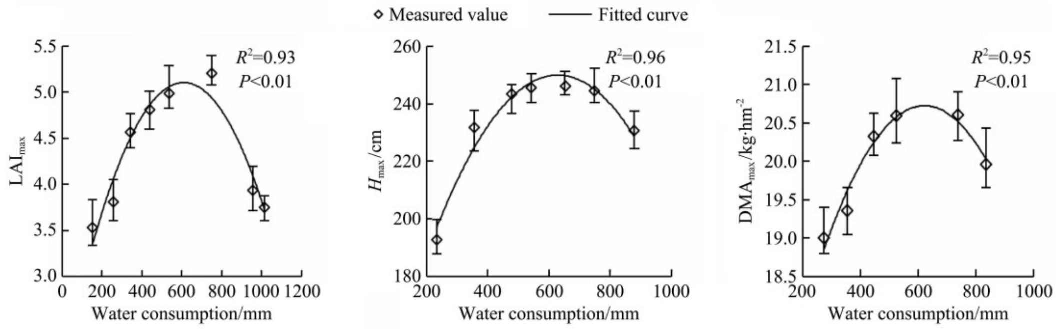
where, W is the water consumption during the growing season, mm. The R^2 values were 0.96, 0.93, and 0.95 for the fitted curves for H_{max}, DMA$_{max}$, and LAI$_{max}$, respectively. The first-order derivative of Equation (13) was set as 0. H_{max} was 250 cm, LAI$_{max}$ was 5.1, and DMA$_{max}$ was 20 725 kg/hm^2 when the total water consumption was 625 mm.

3.4 Relationship between LAI$_{max}$ and HI

The curve obtained for the relationship between HI and LAI$_{max}$ in summer maize is shown in Figure 7. HI increased gradually as LAI$_{max}$ increased to a particular range and then decreased. The relationship between LAI$_{max}$ and HI could be described by the following quadratic polynomial function:

$$\mathrm{HI} = -0.0142\mathrm{LAI}_{max}^{\ 2} + 0.1457\mathrm{LAI}_{max} + 0.1637 \quad (14)$$

where, the R^2 value for the fitted curve was 0.96. The first-order derivative function of Equation (14) was set to 0. The results indicated that HI was maximized by 0.53 when LAI$_{max}$ was 5.13. These findings suggest that LAI$_{max}$ should be maintained near 5.13 to obtain a higher yield in summer maize.



a. LAI_{max} and water consumption b. H_{max} and water consumption c. DMA_{max} and water consumption

Figure 6 Relationships between the maximum leaf area index (LAI_{max}), maximum plant height (H_{max}), maximum dry matter accumulation (DMA_{max}), and water consumption during the growing season

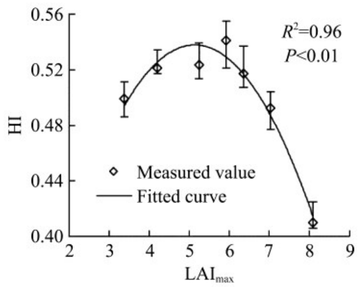


Figure 7 Relationship between the harvest index (HI) and maximum leaf area index (LAI_{max})

3.5 Water-heat coupling relationship for the summer maize yield

The water-heat coupling relationship for the summer maize yield is described by Equation (15) (R^2 = 0.53, p<0.01). Ten sets of non-modeling data were used to verify the water-heat coupling relationship and the results showed that Re = 4.4%. Therefore, the summer maize yield can be predicted using Equation (15):

$$Y = 80145 - 57.56\mathrm{GDD}_{\max} - 181.19W + 4.68\times10^{-4}W^2 + 0.01\mathrm{GDD}_{\max}{}^2 + 0.09W\cdot\mathrm{GDD}_{\max} \quad (15)$$

where, Y is the yield of summer maize, kg/hm^2. The coefficients of W^2 and $GDD_{max}{}^2$ were positive in Equation (15) and the coefficient of the coupling term ($W\cdot GDD_{max}$) was positive.

4 Discussion

4.1 Relationships between relative growth indices, GDD, and RGDD

In this study, the regional logistic models of the relationships between RH, RLAI, and RDMA with GDD and RGDD in summer maize were established for China as an example. The results showed that as GDD and RGDD increased, both RH and RDMA increased gradually and finally tended to stabilize at steady values, whereas RLAI increased initially and then decreased. The increases in H and the foliar area were slow from the seedling to trefoil stage when GDD<500°C and RGDD<0.3. The stem and leaves grew rapidly and LAI increased in a linear manner from the jointing to 12-leaf stage when GDD ranged between 500°C and 1000°C, and RGDD ranged between 0.3 and 0.5[48]. Vegetative and reproductive growth occurred simultaneously, and the rates of increase in H and LAI decreased when GDD ranged between 1000°C and 1300°C, and RGDD ranged between 0.5 and 0.6. H and LAI peaked when GDD was about 1400°C and RGDD ranged between 0.6 and 0.8, which corresponded to the silking stage, and LAI was stable when the maize was in the milk ripening stage. Vegetative growth stopped after silking, mainly due to the allocation of resources to reproductive growth. LAI decreased gradually in the dough stage when GDD>1400°C and RGDD>0.8. The changes in DMA were mainly due to increases in H and foliar growth when GDD<700°C and RGDD<0.4, and the accumulation of dry matter was slow. Vegetative and reproductive growth occurred simultaneously in the maize silking stage when GDD ranged between 1000°C and 1400°C. Thus, the stems, leaves, and fruit grew simultaneously, and the dry matter accumulated rapidly. The grains grew rapidly and DMA continued to increase rapidly when GDD ranged between 1400°C and 1600°C, and RGDD ranged between 0.7 and 0.8. However, the rate of growth was lower than that in the silking stage when the temperature had a major role in reproductive growth. Low rates of photosynthesis or temperatures can lead directly to low maize yields[189]. The rate of increase in DMA decreased when GDD reached 1600°C and RGDD>0.8, and DMA peaked in the maturation stage when GDD increased to about 2000°C.

In addition, the upper and lower envelope parameters were within specific ranges. The parameters for the average curve were selected as the parameters for the final universal model, but the ranges of the upper and lower envelope parameters are suitable for use as the ranges of the summer maize growth model parameters in most areas of China. In the relationship between RH and GDD, the a_0 and a_1 parameters for the upper and lower envelopes differed by 36.2% and 20.9%, respectively. In the relationship between RH and RGDD, the a_0 and a_1 parameters for the upper and lower envelopes differed by 5.5% and 41.3%, respectively. In the relationship between RLAI and GDD, the c_0, c_1, and c_2 parameters for the upper and lower envelopes differed by 38.2%, 26.3%, and 22.4%, respectively. In the relationship between RLAI and RGDD, the c_0, c_1, and c_2 parameters for the upper and lower envelopes differed by 7.3%, 6.1%, and 7.9%, respectively. In the relationship between RDMA and GDD, the b_0 and b_1 parameters for the upper and lower envelopes differed by 40.2% and 5.4%, respectively. In the relationship between RDMA and RGDD, the b_0 and b_1 parameters for the upper and lower envelopes differed by 37.0% and 9.9%, respectively. Therefore, the ranges of the other parameters became smaller when GDD was relativized. The parameters a_1 and b_1 are related to RH, RDMA, and the growth rate of summer maize, and they reflect the sensitivity of H and DMA to changes in the external environment. RGDD can represent the relative growth period for summer maize. The increases in the ranges of a_1 and b_1 indicate that H and DMA are clearly affected by the external environment in the same growth period, and the sensitivity of different growth periods can vary. The logistic model established using GDD does not reflect this feature. Excluding a_1 and b_1, the ranges of the remaining parameters became smaller, thereby demonstrating that the logistic model established using RGDD is more suitable for describing the universal growth characteristics of summer maize. However, the logistic model established using GDD can reflect the response of a crop to temperature in each growth stage, and it is also very important for managing the growth dynamics of crops. Therefore, the two methods should be used together in practical applications in order to accurately predict the growth status of crops.

This universal model has the advantages of simplicity and simple application for most areas of China. In the future, the characteristics of discrete spots near the upper and lower envelope curves will be investigated utilizing data such as tilled soil layer qualities, fertilizer, and illumination intensity. An appropriate method would be sought to ensure that the upper and lower envelope parameters and the average curve are closer to each other, and improve the accuracy of the model.

4.2 Relationships between H_{max}, LAI_{max}, DMA_{max}, and water consumption

Water consumption is the amount of water consumed by crops during the growing season and it is a major factor that affects crop growth. A suitable soil water content and atmospheric humidity can improve crop yield. Thus, quadratic functions were also established between H_{max}, LAI_{max}, DMA_{max}, and water consumption for different regions. These relationships play important roles in regulating growth and predicting the yield of summer maize, thereby improving the model. Summer maize is a dryland crop in these areas and the rainy season occurs during the growing season. The rainfall in normal years can generally satisfy the demand for water from maize. Moderate irrigation can be used in drought years, but the irrigation quota should be moderate and generally about 150 mm[202]. Increasing the amount of irrigation within a particular range can promote transpiration and evaporation, but excessive irrigation may destroy the structure of the soil around the root system, thereby decreasing particle aggregation and aeration. Excessive soil water contents may also affect respiration by crop roots and lead to anaerobic respiration, which is not conducive to the normal growth of maize and it can even lead to lower yields. Many studies have reported that a moderate water deficit can increase the yields of crops[203-208], so irrigation should not be excessive.

In this study, the best values were obtained for all the summer maize growth indices when W was 625 mm. These results are consistent with those reported by Liu et al.[202] regarding the consumption of water by summer maize in northern China.

4.3 Relationship between LAI_{max} and HI

The leaf is the main organ of photosynthesis, which determines the yield to a great extent. The LAI in each growth stage is correlated with the yield in various summer maize cultivars. In this study, the quantitative relationship between LAI_{max} and HI was established. HI tended to increase initially and then decreased. The maximum HI was 0.53 when LAI_{max} was 5.13, thereby indicating that more nutrients were distributed to the plant organs, which led to a higher yield when LAI_{max} exceeded the range. LAI was excessively high beyond this range, which indicates that the leaves would absorb more nutrients than necessary and that the grain yield would decrease due to the lower supply of nutrients. Therefore, LAI_{max} should be maintained near 5.13 to obtain higher summer maize yields.

4.4 Water-heat coupling relationship for summer maize yield

Water-heat coupling is an important part of the soil-plant-atmosphere continuum, which is linked to transpiration, evaporation, soil moisture, and atmospheric temperature. Theoretically, moisture and temperature both have specific thresholds with respect to crop growth, where both have positive effects on crop growth within these thresholds, which can lead to higher crop yields. The coefficients of W^2 and GDD_{max}^2 were positive in Equation (15), thereby indicating that the summer maize yield was characterized as increasing initially and then decreasing with the increase in GDD_{max} or W. The coefficient of the coupling term ($W \cdot GDD_{max}$) was positive, which suggests that water-heat coupling had a synergistic effect on the summer maize yield.

In this work, universal models were proposed for predicting summer maize growth in China. The logistic model was a deterministic function, but hard to accurately simulate the data points of special cases such as the different irrigation and fertilization schedule, extreme weather, plant diseases, and insect pests. Therefore, the simulation accuracy of the universal model under the above specific cases needs to be further improved in future work.

5 Conclusions

The plant height (H), leaf area index (LAI), and dry matter accumulation (DMA) were strongly correlated with the growing degree days (GDD) and relative growing degree days (RGDD). The harvest index (HI) was correlated with LAI, and LAI had a clear functional relationship with water consumption. Thus, a quantitative model was established to synthetically analyze the main growth characteristics of summer maize based on water consumption, GDD, and RGDD. H, LAI, and DMA could be predicted using GDD or RGDD for the corresponding growing season. RGDD was more suitable than GDD for establishing a logistic model to describe the changes in RH, RLAI, and RDMA. LAI_{max} and HI could be predicted using a suitable water consumption estimate. The relationships between the yield, GDD_{max}, and the water consumption during the growing season (W) could be described by a binary quadratic equation, thereby allowing the summer maize yield to be predicted using GDD_{max} and W.

Acknowledgements

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[References]

[1] Walther G R, Post E, Convey P, Menzel A, Parmesan C, Beebee T J C. Ecological responses to recent climate change. Nature, 2002; 416(6879): 389–395.

[2] Parry M A J, Lea P J. Food security and drought. Annals of Applied Biology, 2009; 155(3): 299–300.

[3] Tilman D, Balzer C, Hill J, Befort B L. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences, 2011; 108(50): 20260–20264.

[4] Tai A P K, Martin M V, Heald C L. Threat to future global food security from climate change and ozone air pollution. Nature Climate Change, 2014; 4(9): 817–821.

[5] Ahmed K F, Wang G L, Yu M, Koo J, You L Z. Potential impact of climate change on cereal crop yield in West Africa. Climate Change, 2015; 133(2): 321–334.

[6] Kumar M. Impact of climate change on crop yield and role of model for achieving food security. Environmental Monitoring and Assessment, 2016; 188(8): 1–14.

[7] Rockström J, Steffen W, Noone K, Persson Å, Chapin F S, Lambin E F. A safe operating space for humanity. Nature, 2009; 461(7263): 472–475.

[8] Wei T, Glomsrød S, Zhang T. Extreme weather, food security and the capacity to adapt - the case of crops in China. Food Security, 2015; 9(3):

523–535.
[9] FAO, FAOSTAT Database. 2016. Available: http://faostat.fao.org/. Accessed on [2020-10-05].
[10] Cui J, Yan P, Wang X, Yang J, Li Z, Yang X. Integrated assessment of economic and environmental consequences of shifting cropping system from wheat-maize to monocropped maize in the North China Plain. Journal of Cleaner Production, 2018; 193: 524–532.
[11] Haarhoff S J, Swanepoel P A. Plant population and maize grain yield: a global systematic review of rainfed trials. Crop Science, 2018; 58: 1819–1829.
[12] FAO, FAOSTAT Database. 2018. Available: http://www.fao.org/faostat/en/#data/QC. Accessed on [2020-10-05].
[13] Zhao J F, Guo J P, Xu Y H, Mu J. Effects of climate change on cultivation patterns of spring maize and its climatic suitability in Northeast China. Agriculture, Ecosystems and Environment, 2015; 202: 178–187.
[14] He Q J, Zhou G S. Climate-associated distribution of summer maize in China from 1961 to 2010. Agriculture, Ecosystems and Environment, 2016; 232: 326–335.
[15] China Statistical Yearbook, China Statistical Press, 2018. Available: http://www.stats.gov.cn/tjsj/ndsj/2018/indexch.htm. Accessed on [2020-10-05]. (in Chinese)
[16] Li S K, Wang C T. Evolution and development of maize production techniques in China. Scientia Agricultura Sinica, 2009; 42: 1941–1951. (in Chinese)
[17] Meng Q F, Hou P, Wu L, Chen X P, Cui Z L, Zhang F S. Understanding production potentials and yield gaps in intensive maize production in China. Field Crop Research, 2013; 143: 91–97.
[18] Liu B H, Chen X P, Meng Q F, Yang H S, van Wart J. Estimating maize yield potential and yield gap with agro-climatic zones in China—distinguish irrigated and rainfed conditions. Agricultural and Forest Meteorology, 2017; 239: 108–117.
[19] de Wit C T. Photosynthesis of leaf canopies Netherland. The Journal of Agricultural Science, 1965; 13: 57–59.
[20] Atzberger C. Advances in remote sensing of agriculture: context description, existing operational monitoring systems and major information needs. Remote Sensing, 2013; 5(2): 949–981.
[21] White J W, Hoogenboom G, Kimball B A, Wall G W. Methodologies for simulating impacts of climate change on crop production. Field Crops Research, 2011; 124(3): 357–368.
[22] Mo X, Liu S, Lin Z, Xu Y, Xiang Y, McVicar T R. Prediction of crop yield, water consumption and water use efficiency with a SVAT-crop growth model using remotely sensed data on the North China Plain. Ecological Modelling, 2005; 183(2-3): 301–322.
[23] Jones C A, Kiniry J R, Dyke P T, Farmer D B, Godwin D C, Parker S H. CERES-Maize: A simulation model of maize growth and development. Texas A&M University Press, 1986; 194p.
[24] Williams J, Jones C, Kiniry J, Spanel D. The EPIC crop growth model. Transactions of the ASAE, 1989; 32: 497–511.
[25] Jones J W, Hoogenboom G, Porter C H, Boote K J, Batchelor W D, Hunt L A. The DSSAT cropping system model. European Journal of Agronomy, 2003; 18: 235–265.
[26] Keating B A, Carberry P S, Hammer G L, Probert M E, Robertson M J, Holzworth D. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy, 2003; 18: 267–288.
[27] Stöckle C O, Kemanian A R, Nelson R L, Adam J C, Sommer R, Carlson B. CropSyst model evolution: from field to regional to global scales and from research to decision support systems. Environmental Modelling and Software, 2014; 62: 361–369.
[28] Yang H, Grassini P, Cassman K G, Aiken R M, Coyne P I. Improvements to the hybrid-maize model for simulating maize yields in harsh rainfed environments. Field Crops Research, 2017; 204: 180–190.
[29] Malik W, Isla R, Dechmi F. DSSAT-CERES-maize modelling to improve irrigation and nitrogen management practices under Mediterranean conditions. Agricultural Water Management, 2019; 213: 298–308.
[30] Peng B, Guan K, Chen M, Lawrence D M, Pokhrel Y, Suyker A. Improving maize growth processes in the community land model: Implementation and evaluation. Agricultural and Forest Meteorology, 2018; 250: 64–89.
[31] Xu Y, Zhou M Y, Xue Y F. Spatial variability and relationships of rice leaf area index and yield. Transactions of the CSAE, 2006; 22(5): 10–14. (in Chinese)
[32] Wu Y G, Wu C L, Qin B P, Wang Z L, Huang W, Yang M, et al. Diversity of 175 wheat varieties from Yellow and Huai River Valleys facultative wheat zone and association of SSR markers with plant height and yield related traits. Acta Agronomica Sinica, 2012; 38(6): 1018–1028. (in Chinese)
[33] Khan A, Wang L S, Ali Stung S A, Hafeez A, Yang G Z. Optimal planting density and sowing date can improve cotton yield by maintaining reproductive organ biomass and enhancing potassium uptake. Field Crops Research, 2017; 214: 164–174.
[34] Ma L, Wang Q J, Fan J. Characteristics and models of spring wheat growth by a modified logistic model in the desert oasis conditions. Journal of Food, Agriculture & Environment, 2013; 11(1): 614–624.
[35] Wang X X, Wang Q J, Fan J, Sun L J. Logistic model analysis of winter wheat growth on China's Loess Plateau. Canadian Journal of Plant Science, 2014; 94(8): 1471–1479.
[36] Liu Y, Su L, Wang Q, Zhang J, Shan Y, Deng M. Comprehensive and quantitative analysis of growth characteristics of winter wheat in China based on growing degree days. Advances in Agronomy, 2019; 159: 237–273.
[37] Wang K, Su L J, Wang Q J. Cotton growth model under drip irrigation with film mulching: A case study of Xinjiang, China. Agronomy Journal, 2021; 113(3): 2417–2436.
[38] Wang J, Feng H, Wang N J, Dong Q G, Chu X S, Zhou L F. Effects of ridge-furrow planting with plastic film mulching on summer maize growth and soil water. Journal of Soil and Water Conservation, 2018; 32(2): 110–119.
[39] Fang H, Li Y N, Gu X B, Yin M H, Yang J Y. Fitting and analysis of grain filling of summer maize under combination of film mulching and nitrogen fertilizer. Transactions of the CSAM, 2018; 49(8): 245–252. (in Chinese)
[40] Richards F J. A flexible growth function for empirical use. Journal of Experimental Botany, 1959; 10(2): 290–301.
[41] Jagtap S S, Jones J W. Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production. Agriculture Ecosystems and Environment, 2002; 93(1): 73–85.
[42] Jin X L, Kumar L, Li Z H, Feng H K, Xu X G, Yang G J, et al. A review of data assimilation of remote sensing and crop models. European Journal of Agronomy, 2018; 92: 141–152.
[43] Anandhi A. Growing degree days - ecosystem indicator for changing diurnal temperatures and their impact on maize growth stages in Kansas. Ecological Indicators, 2016; 61: 149–158.
[44] Wang J Y. A critique of the heat unit approach to plant response studies. Ecology, 1960; 41(4): 785–790. (in Chinese)
[45] Gregory S. Accumulated temperature maps of the British Isles. Transactions and Papers (Institute of British Geographers), 1954; 20(20): 59–73.
[46] McMaster G S, Wilhelm W W. Growing degree-days: one equation, two interpretations. Agricutural and Forest Meteorology, 1997; 87(4): 291–300.
[47] Stewart D W, Dwyer L M, Carrigan L L. Phenological temperature response of maize. Agronomy Journal, 1998; 90(1): 73–79.
[48] Lin Z H, Xiang Y Q, Mo X G, Li J, Wang L. Normalized leaf area index model for summer maize. Chinese Journal of Eco-Agriculture, 2003; 11(4): 69–72. (in Chinese)
[49] Wang L, Xie D T, Liu H L, Yang J. A universal growth model for maize leaf area index. Journal of Southwest Agricultural University, 2004; 3: 303–306, 311. (in Chinese)
[50] Zhang X D, Cai H J, Fu Y J, Wang J. Study on leaf area index of summer maize in loess areas. Agricultural Research in the Arid Areas, 2006; 24(2): 25–29. (in Chinese)
[51] Wang X. Rational application of logistic equation in the dynamic simulation of dry matter accumulation in crops. Chinese Journal of Agrometeorology, 1986; 1: 14–19. (in Chinese)
[52] Bonhomme R. Bases and limits to using “degree·day” units. European Journal of Agronomy, 2000; 13(1): 1–10.
[53] Haggard G B, Weindorf D, Cacovean H, Rusu T, Lofton J. Analysis of growing degree days in the Transylvanian Plain, Romania. Studia Universitatis Babes-Bolyai, Geographia, 2010; 2: 13–20.
[54] Bollero G A, Bullock D G, Hollinger S E. Soil temperature and planting date effects on maize yield, leaf area, and plant development. Agronomy Journal, 1996; 88(3): 385–390.
[55] Ni Q. Physiological basis of crop yield variation. Beijing: Science

Press, 1960; 123p.

[56] Donald C M. In search of yield. J Aust Inst Agr Sci, 1962; 28: 171–178.

[57] Hay R K M. Harvest index: a review of its use in plant breeding and crop physiology. Annals of Applied Biology, 1995; 126(1): 197–216.

[58] Pandey R K, Maranville J W. Deficit irrigation and nitrogen effects on maize in a Sahelian environment. I. Grain yield and yield components. Agricultural Water Management, 2000; 46(1): 1–13.

[59] Xu R, Dai J, Luo W, Yin X, Li Y, Tai X, et al. A photothermal model of leaf area index for greenhouse crops. Agricultural and Forest Meteorology, 2010; 150(4): 541–552.

[60] Davoodi E, Ghasemieh H, Batelaan O, Abdollahi K. Spatial-temporal simulation of LAI on basis of rainfall and growing degree days. Remote Sensing, 2017; 9(12): 1–17.

[61] Chen Y, Zhang Z, Tao F, Palosuo T, Rötter R P. Impacts of heat stress on leaf area index and growth duration of winter wheat in the North China Plain. Field Crop Research, 2018; 222: 230–237.

[62] Fang H, Liang S, Hoogenboom G. Integration of MODIS LAI and vegetation index products with the CSM-CERES-Maize model for maize yield estimation. International Journal of Remote Sensing, 2011; 32(4): 1039–1065.

[63] Labbafi M, Khalaj H, Allahdadi I, Nadjafi F, Akbari G A. Using models for estimation of leaf area index in Cucurbita pepo L. Journal of the Saudi Society of Agricultural Sciences, 2017; 18(1): 55–60.

[64] Xu Y X, Wei Z B, Wang T L. Effects of different fertilizer methods on growth, development and yield of summer maize. Anhui Agricultural Science Bulletin, 2009; 15(18): 54–55. (in Chinese)

[65] Zheng Y Q, Wei Z B, Wang L W. Effect of no-tillage on growth index and yield of summer maize. Anhui Agricultural Science Bulletin, 2011; 17(18): 38, 101. (in Chinese)

[66] Song S, Song Y, Li J. A simulation study on high yield cultivation system of summer maize. Journal of Henan Vocation-technical Teachers College, 1992; 1: 12–16. (in Chinese)

[67] Liu Z D, Xiao J F, Nan J Q, Feng Y H. Effect of sowing date on growth stages, morphological index and yield of summer maize. Acta Agriculturae Boreali-Occidentalis Sinica, 2010; 19(6): 91–94. (in Chinese)

[68] Li J L, Zhang H, Cao S C. Dynamic monitoring on the summer maize growth based on satellite remote sensing. Journal of Maize Sciences, 2013; 21(3): 149–153. (in Chinese).

[69] Xu H T, Xu B, Wang Y H, Wang C Y, Zhang H S. Effects of ridge cultivation on physiological indexes and yield components of summer maize. Hunan Agricultural Sciences, 2008; 3: 49–51. (in Chinese)

[70] Zhao X, Liu J B, Wang Z H, Huang L, Zhang Z H. Study on growth and yield of summer maize (*Zea mays* L.) with different sustained controlled release fertilizers. Chinese Agricultural Science Bulletin, 2008; 6: 247–249. (in Chinese)

[71] Liu Z, W H, Wang G. A study on the irrigation way of summer maize in sandy soil. Journal of Desert Research, 1999; 2: 74–77. (in Chinese)

[72] Kang L, Qi X, Ma Y, Qiao D, Li P, Huang Z. Impact of reclaimed water irrigation on summer maize development under different underground water level. Journal of Irrigation and Drainage, 2007; 5: 43–46. (in Chinese)

[73] Xiao J, Liu Z, Liu Z, Nan J. Effects of drought at different growth stages and different water availabilities on growth and water consumption characteristics of summer maize. Journal of Maize Sciences, 2011; 19(4): 54–58, 64. (in Chinese)

[74] Wang C, Yang W. Character studying in maize plants and yield impact about different fertilization methods. Chinese Agricultural Science Bulletin, 2011; 27(9): 305–308. (in Chinese)

[75] Yang N, Sun Z M, Zhang S S, Wang L C, Kong L G, Zheng G X, et al. Study on screening of different varieties of summer maize in Zaozhuang City. Agricultural Science and Technology Newsletter, 2017; 8: 132–138. (in Chinese).

[76] Xu C Z, Kong X M, Yang H B, Yan L, Wang F H. Effect of sowing in hills on growth and development and yield components of summer maize. Journal of Maize Sciences, 2006; 5: 104–106, 110. (in Chinese)

[77] Xu Y, Li M H, Li H, Jiang P. Effects of drought on the growth and yield of maize at different stages over the North China plain. Journal of Meteorology and Environment, 2017; 33(1): 108–112. (in Chinese)

[78] Bian D H, Zhang R D, Duan L S, Li J M, Li Z H. Effects of partial spraying of plant growth regulator on canopy structure, chlorophyll fluorescence characteristic and yield of summer maize (*Zea mays* L.). Acta Agriculturae Boreali-Sinica, 2011; 26(3): 139–145. (in Chinese)

[79] Song L B, Yao N, Feng H, Bai J, Wu S F, He J Q. Effects of water stresses at different growth stages on development and yields of summer maize in arid region. Journal of Maize Sciences, 2016; 24(1): 63–73. (in Chinese)

[80] Wang C Z, Yu Z R, Sun D F, Liu Y, Liu Y H. Analysis on the factors affecting summer maize canopy-air temperature difference. Chinese Journal of Soil Science, 2006; 37(4): 651–658. (in Chinese)

[81] Wen L L, Liu W Z, Li S W, Wen H D. Effects of water and fertilizer coupling on biological characteristics and yields of summer maize. Journal of Agricultural University of Hebei, 2012; 35(3): 14–19. (in Chinese)

[82] Li Z, Wang P, Marion B Z, Claupein W. Effects of the optimized fertilization and traditional fertilization on growth, development and yield of summer maize. Journal of Maize Sciences, 2003; 3: 90–93, 97. (in Chinese)

[83] Zou H, Huang X F, Gong S H. Effects of water deficit on soil moisture and temperature regimes in subsurface drip irrigated summer maizefield. Transactions of the CSAM, 2012; 43(9): 72–77. (in Chinese)

[84] Qi Z M, Feng S Y, Huang G H, Cha G F. Experimental study on effects of irrigation water quality on plant growth of summer maize. Journal of Irrigation and Drainage, 2003; 22(2): 36–38. (in Chinese)

[85] Zhou L, Jiang Y, Chen F, Zeng Z. Effects of soybean-maize rotation and fertilization on the agronomic trait and grain yield of maize. Journal of China Agricultural University, 2013; 18(6): 61–67. (in Chinese)

[86] Xiao J F, Nan J Q, Liu Z D, Yu J H. Study on the relationship between yield and yield composition of summer maize with different groundwater depth. Agricultural Research in the Arid Areas, 2010; 28(6): 36–39. (in Chinese)

[87] Yu J H, Ding B R, Chen J, Zhang H B, Shi X M. Effects of different groundwater levels on growth and yield components of maize. Water Saving Irrigation, 2010; 11: 43–45. (in Chinese)

[88] Liu Z D, Xiao J F, Yu J H, Nan J Q, Liu Z G. Effects of different groundwater depths on root and shoot growth and water consumption of summer maize. Journal of Irrigation and Drainage, 2011; 30(4): 44–47. (in Chinese)

[89] Sui H, Sun X H, Li X G, Xu E H, Liu Q. Effect of fertilization on plant and yield of summer maize under highland stress. Science and Technology of Tianjin Agriculture and Forestry, 2008; 3: 8–10. (in Chinese)

[90] Zhu B G, Zhang C F, Wang N, Meng Q, Jia H B, Kuang E. Effects of different nitrogen topdressing methods on correlated character and yield of maize in cold zone. Journal of Nuclear Agricultural Sciences, 2015; 29(9): 1806–1812. (in Chinese)

[91] Han X, Wang L, Wang Y P. Canopy interception of summer maize and its influencing factors under natural rainfall. Scientia Agricultura Sinica, 2014; 47(8): 1541–1549. (in Chinese)

[92] Li Q, Zhang D, Wang D, Wang Z. Effect of planting density on yield and components of Fanyu 298. China Seed Industry, 2017; 7: 61–63. (in Chinese)

[93] Yang Y H, Wu J C, Ding J L, Zhang J M, Gao C M, Pan X Y, et al. Simulation and verification of the effects of DSSAT model in maize growth process under long-term conservation tillage and soil improvement measures. Chinese Journal of Agrometeorogy, 2017; 46(12): 149–158. (in Chinese)

[94] Zhang H. Indirect measurement of leaf area index by shading rate. Irrigation and Drainage, 1997; 1: 43–44. (in Chinese)

[95] Xie R, Li C, Zhou S, Zhang G. Study on growth mechanism of super-high yield summer maize. Journal of Henan Agricultural University, 1999; 1: 13–18. (in Chinese)

[96] Zhou S Z, Li C H, Chang S M, Lian Y X, Liu K. Effects of ridge culture on summer maize ecological environment and growth development. Journal of Henan Agricultural University, 2000; 34(3): 206–209. (in Chinese)

[97] Fu X, Zhang H, Jia J, Du L, Fu J, Zhao M. Yield performance and resources use efficiency of winter wheat and summer maize in double late-cropping system. Acta Agronomica Sinica, 2009; 35(9): 1708–1714. (in Chinese)

[98] Guo Z S, Huangpu Z Q, Zhang S J, Liu Y X, Hou L X. Study on population physiological indices of summer maize with high yield on Eastern Henan Plain. Hubei Agricultural Sciences, 2013; 52(17): 4054–4057. (in Chinese)

[99] Guo S Y, Shang S, Zhang Y, Lu G Y, Wang X F, Tang Q N. Effects of

different cultivation and water retaining agent on summer maize growth and development. Chinese Agricultural Science Bulletin, 2014; 30(24): 93–97. (in Chinese)
[100] Shang S, Jiang X J, Tang Q N, Guo S Y, Zhang Y, Lu G Y. Effect of planting density on leaf area index and mechanized harvest grain quality of maize variety "Qiaoyu 8". Chinese Agricultural Science Bulletin, 2017; 33(36): 25–29. (in Chinese)
[101] Ma P P, Zhang Z J, Gao Z L, Feng Y H. Experimental study on high moisture content of summer maize in Eastern Henan Province. Henan Water Resources & South-to-North Water Diversion, 2013; 16: 104–105. (in Chinese)
[102] Liu W C, Wang Y L, Ma R X. Studies on productivity and main physiological index of differential types of summer corns. Journal of Henan Agricultural Sciences, 2003; 32(3): 10–13. (in Chinese)
[103] Zhang Y Y, Li Y J, Lu D W. Study on the absorption, accumulation and distribution of nitrogen and phosphorus in summer maize in North Henan Province. Journal of Anhui Agricultural Sciences, 2018; 46(17): 52–55. (in Chinese)
[104] Li C H, Su Z L, Shi J Z, Zhuo D Z. The characteristics of population ecology and physiology of high-yielding summer maize. Journal of Henan Agricultural University, 1991; 4: 379–386. (in Chinese)
[105] Wang S, Chen H, Gao C, Li X. Experimental study on growth and yield of summer maize under different planting patterns. Journal of Irrigation and Drainage, 2011; 30(3): 65–67. (in Chinese)
[106] Liang X W, Zhao B X, Wan H L, Lei X B, Chen R L, Li L, et al. Study on group dynamic indexes of 'Luoyu 863'of maize. Chinese Agricultural Science Bulletin, 2013; 29(36): 96–101. (in Chinese)
[107] Jin S C, Li L, Wan H L, Cai S L, Wei Y Q, Zhao H L. Study on physiological indexes of colony of new maize variety Luoyu 818. Acta Agriculturae Jiangxi, 2014; 26(6): 11–14. (in Chinese)
[108] Zhang Y E, Zhao Y L, Wang Q, Li C H. The comparison between the photosynthetic characteristics of different maize hybrids in overabundant rain and poor sunshine year in later growth stage. Journal of Maize Sciences, 2005; 3: 67–70, 73. (in Chinese)
[109] Wang Q, Li C, Zhang Y, Hao S, Liu S. Research on chlorophyll fluorescence characteristic of summer maize in the late growth stage in different soil texture. Journal of Anhui Agricultural Sciences, 2006; 21: 5476–5479. (in Chinese)
[110] Zhang S Q, Zhang J T, Li J X, Cheng Y Z, Li G Q. Calibration and validation of WOFOST in main maize- producing region in Henan. Journal of Henan Agricultural Sciences, 2014; 43(8): 152–156. (in Chinese)
[111] Shao Y, Zeng J, Guo Y, Guo Q, Wang T, Wei L. Effects of planting patterns with high density on chlorophyll, fluorescence and yield of summer maize. Agricultural Research in the Arid Areas, 2016; 34(5): 85–90. (in Chinese)
[112] Lu H, Li Y, Mei Z, Yan L, Li B, Xu Y. Effects of different sowing dates on agronomic characters and yield of Xundan 20. Bulletin of Agricultural Science and Technology, 2010; 12: 134–136. (in Chinese)
[113] Wang X, Liu T, Dong P, Li C, Dai X. Canopy structure and light energy utilization of high-yield maize hybrids. Journal of Henan Agricultural Sciences, 2010; 4: 13–15. (in Chinese)
[114] Chang J, Zhang G, Li Y, Zhu Z, Li B. Effects of recommended fertilization on growth. development, yield and economic benefit of superhigh-yielding summer maize. Acta Agriculturae Jiangxi, 2011; 23(7): 105–107. (in Chinese)
[115] Zhang S, Zhang C. Correlations between the main characteristics and yield of different summer maize hybrids. Chinese Agricultural Science Bulletin, 2014; 30(27): 15–20. (in Chinese)
[116] Ma G S, Xue J Q, Lu H D. Study on physiological indexes of new maize variety Shaandan 8806 high yield population. Journal of Maize Sciences, 2005; 13(3): 83–85. (in Chinese)
[117] Jin Y Z, Xie R Z, Feng J K, Li S K, Gao S J, Ding L M. Research on the effect of summer maize yield under conservation tillage pattern in North China Plain. Journal of Maize Sciences, 2008; 16(4): 143–146. (in Chinese)
[118] Chen S, Xu H. Effects of community density on characters index and yield of summer maize in Huanghuai Area. Journal of Anhui Agricultural Sciences, 2011; 39(26): 15900–15901, 15910. (in Chinese).
[119] Xu H T, Wang C Y, Liu F, Zheng J H, Shi S T. Effects of sustained controlled release fertilizer on main production characters of summer maize Chuangyu 198 and topsoil properties. Journal of Hebei Agricultural Sciences, 2012; 16(10): 66–70. (in Chinese)
[120] Xu H T, Chen G J. Effects of community efficiency on the photosynthetic-physiological characters and seed yield of summer maize. Journal of Henan Institute of Science and Technology (Natural Sciences Edition), 2014; 42(3): 8–11, 15. (in Chinese)
[121] Hou H P, Wang R Q, Sui H, Zhao M. Response characteristics of different genotypes of summer maize to planting density. Science and Technology of Tianjin Agriculture and Forestry, 2014; 1: 1–3. (in Chinese).
[122] Hong D F, Chen H, Tang Z H, Ma J F, Wei X Y, Ma Y, et al. Effects of different tillage methods and straw returning on maize plant characters and grain yield. Shandong Agricultural Sciences, 2015; 47(1): 26–28. (in Chinese)
[123] Wang X H, Jin G L, Li C Y, Lyu G M, Yan H N. Application effect of tricolor ecological fungi fertilizer on summer maize production. Henan Agriculture, 2012; 13: 16–20. (in Chinese).
[124] Lü S M, Liu T G, Zhao H J. Effects of different biogas slurry application rates on summer maize yield. China Biogas, 2015; 33(4): 77–81. (in Chinese)
[125] Zhu Y X, Xiao J F, Feng Y H. Experimental study on planting density of summer maize in East Henan Province in 2010. Henan Water Resources and South-to-North Water Diversion, 2011; 12: 51–53. (in Chinese)
[126] Wang Z J, Yang K J, Xi Z H. Effect of sowing date on photosynthetic characteristics and yield formation of waxy maize. Anhui Agricultural Science Bulletin, 2015; 21(6): 33–34. (in Chinese)
[127] Zhang P F. Effects of planting density on the yield and leaf area index of Demeiya 3. Journal of Anhui Agricultural Sciences, 2016; 44(30): 29–30. (in Chinese)
[128] Liu Q H, Zhang J M, Li F, Dong S T. Experimental study on transplanting of summer maize seedling with soil in plastic disk. Tillage and Cultivation, 1999; 5: 35–37. (in Chinese)
[129] Li L L, Zhang J W, Liu W, Lyu P, Liu P, Dong S T. Study on high yield characteristics of new maize variety Denghai661. Journal of Maize Sciences, 2011; 19(5): 83–86. (in Chinese)
[130] Jin L B, Zhang J W, Li B, Cui H Y, Dong S T, Liu P, et al. Canopy structure and photosynthetic characteristics of high yield and high nitrogen efficiency summer maize. Scientia Agricultura Sinica, 2013; 46(12): 2430–2439. (in Chinese)
[131] Ren B C, Zhu Y L, Li X, Fan X, Dong S T, Zhao B, et al. Effects of waterlogging on photosynthetic characteristics of summer maize under field conditions. Acta Agronomica Sinica, 2015; 41(2): 329–338. (in Chinese)
[132] Zhang Z, Zhong W W, Wang X Y, Chen Y H, Zhou X B. Effect of cultivation measures of previous winter wheat on following summer maize photosynthesis characteristics and yield. Acta Agriculturae Boreali-Sinica, 2017; 32(4): 155–161. (in Chinese)
[133] Xu M R, Liu K, Zhang J W, Ren B Z. Effects of phosphorus levels on growth and yield of summer maize. Shandong Agricultural Sciences, 2018; 50(1): 86–90. (in Chinese)
[134] Feng S Z, Wang S W, Peng M X, Liu N, Zhao G T. Effects of different planting densities on grain yield, LAI and dry matter accumulation of summer maize. Acta Agriculturae Jiangxi, 2015; 27(3): 1–5, 22. (in Chinese)
[135] Feng S Z, Peng M X, Kong J H, Liu N, Zhao L, Wang S W, et al. Effects of nitrogen fertilizer application on dry matter accumulation. Leaf area index and yield of high-yielding summer maize. Acta Agriculturae Jiangxi, 2015; 27(2): 1–6. (in Chinese).
[136] Xu Y, Zhou M Y, Xue Y F. Spatial variability and relationships of rice leaf area index and yield. Transactions of the CSAE, 2006; 22(5): 10–14. (in Chinese)
[137] Zhao Y Y, Dong J, Cui Y F. Effect of water and fertilizer coupling on summer maize. Shandong Agricultural Sciences, 2011; 12: 82–83. (in Chinese)
[138] Song C L, Han C W, Zhang C C. Effects of plant density on agronomic characters, dry matter accumulation and yield of summer corn. Shandong Agricultural Sciences, 2013; 45(4): 55–60. (in Chinese)
[139] Ren Y Y, Zhang L Q, Kong X M, Shao G Q, Liu G W, Gao Y Y, et al. Effects of different tillage and nitrogen application on growth, development and yield of summer maize. Agricultural Science and Technology Newsletter, 2016; 7: 67–70. (in Chinese)
[140] Wang X Z, Zhang J, Li H M, Wu J H, Wang L J, Bai H L, et al. Effects of different controlled release fertilizer types and application rates on yield of summer maize. Agricultural Science and Technology Newsletter,

2016; 7: 63–66. (in Chinese)
[141] Wen L Y, Song X Y, Liu S T. Effect of water and fertilizer coupling on foliar index and biomass at different growth stages of summer maize. Chinese Agricultural Science Bulletin, 2014; 30(21): 89–94. (in Chinese)
[142] Wang J J, He H J, Zhang Z K, Dai Z M, Tan Y Q, Chang P P. Effects of wide-narrow row interlaced thick-planting pattern on photosynthetic characteristic and yield in summer maize. Journal of Maize Sciences, 2017; 25(3): 65–72, 79. (in Chinese)
[143] Dong X W, Liu S T. A study of canopy apparent photosynthesis property in summer maize with superhigh yield. Acta Agriculturae Boreall-Sinica, 1999; 2: 36–41. (in Chinese)
[144] Dong X W, Liu G, Zhang H, Yin Y. Effect of irrigation water content on photosynthetic capacity and yield of summer maize. Maize Sciences, 2000; 4: 53–56. (in Chinese)
[145] Sui F, Ge T, Liu P, Lyu Y, Zhou G. Studies on accumulation, translocation and redistribution of carbon in summer maize under drought. Chinese Journal of Eco-Agriculture, 2006; 3: 234–237. (in Chinese)
[146] Zhang H. Effects of different plant spacing on growth and yield of summer maize. Agricultural Science and Technology Newsletter, 2018; 3: 76–79. (in Chinese)
[147] Wu S, Zheng H. Effects of different seed coating treatments on leaf area index of maize with different sowing date. Anhui Agricultural Science Bulletin, 2010; 16(24): 75–87. (in Chinese)
[148] Zheng Y, Zhang L, Cui Z, Wu D. Effects of planting density on canopy structure and photosynthetic potential of summer maize with different plant types. Jiangsu Agricultural Sciences, 2010; 3: 116–118, 121. (in Chinese)
[149] Cao D, Wang H, Liu G, Wang J, Ren Y, Zhang K. Effects of sulfur element on photosynthetic characteristics and yield of maize. Journal of Maize Sciences, 2017; 25(2): 68–73, 80. (in Chinese)
[150] Huang Z, Shen L, Sun G, Cao Y, Bao Y, Liang X. Study on leaf area and dry matter accumulation and distribution in super high-yield maize. Journal of Anhui Agricultural Sciences, 2007; 8: 2227–2228, 2230. (in Chinese).
[151] Du D, Fang X, Liu Z, Lyu D, Zhao F, Yu Z. Effect of different planting density on yield of Jidan 631 Maize. Modern Agricultural Science and Technology, 2017; 15: 25–26. (in Chinese)
[152] Gu Y, Hu W, Wang N, Chen X, Liang X, Yue Y. Canopy physiological parameter in maize with different yield potentials. Journal of Maize Sciences, 2011; 19(5): 73–77. (in Chinese)
[153] Yue Y, Wu S, Gu Y, Huang H, Zhang Y, Yu F. Comparative study on leaf area index and yield composition of compact and flat maize. Jilin Agriculture, 2011; 1: 35–36. (in Chinese)
[154] Lin X, Li C. Study on physiological characteristics and high yield potential of Xundan 29. China Seed Industry, 2011; 7: 42–44. (in Chinese)
[155] Lu H, Xue J, Ma G. Study on different groups receive light posture and photosynthesis character of summer maize. Journal of Maize Sciences, 2008; 4: 100–104. (in Chinese)
[156] Ma Y, Xue J, Zhang R, Zhang L, Hao Y, Sun J. Relationship between dry matter accumulation and distribution to yield of different maize cultivars. Guangdong Agricultural Sciences, 2010; 37(3): 36–40. (in Chinese)
[157] Wang Z, Luan Y, Wen G, Dong P. Research on the leaf area index, dry matter accumulation with yield of seed maize under different irrigation methods. Agricultural Research in the Arid Areas, 2017; 35(6): 27–31. (in Chinese)
[158] Liu P, Xu S, Du Q, Wang K. Effects of sowing date on yield and photosynthetic characteristics of summer maize. Journal of Nanjing Agricultural University, 2016; 5: 722–729. (in Chinese)
[159] Ding C, Shen S, Tao S, Li M, Yu L. Responses of root-crown and leaf water use efficiency to soil moisture in Maize. Jiangsu Agricultural Sciences, 2015; 10: 108–111. (in Chinese)
[160] Cui Y H, Luo Y L, Li B H. Relations of grain yield and photosynthetic characteristics on upright-leaf summer corn (*Zea mays* L.). Maize Sciences, 1994; 2: 52–57. (in Chinese)
[161] Cao C Y, Zheng C L, Li K J, Ma J Y, Cui Y H. Effect of long-term fertilization on photosynthetic property and yield of summer maize (*Zea mays* L.). Chinese Journal of Eco-Agriculture, 2009; 17(6): 1074–1079. (in Chinese)
[162] Lü L H, Tao H B, Xia L K, Zhang Y J, Zhao M, Zhao J R, et al. Canopy structure and photosynthetic characteristics of summer maize under different planting densities. Acta Agronomica Sinica, 2008; 34(3): 447–455. (in Chinese)
[163] Lü L H, Zhao M, Zhao J R, Tao H B, Wang P. Canopy structure and photosynthesis of summer maize under different nitrogen fertilizer application rates. Scientia Agricultura Sinica, 2008; 34(9): 2624–2632. (in Chinese)
[164] Huang S B, Xu L N, Tao H B, Wang Y Q, Qi L P, Wang P. High yield canopy structure of summer maize in North China Plain. Journal of Maize Sciences, 2012; 20(5): 147–152. (in Chinese)
[165] Jin P Y, Ren W, Tao H B, Wang P. Effects of subsoiling on dry matter production, photosynthetic performance and root development of summer maize. Journal of Maize Sciences, 2014; 22(1): 114–120. (in Chinese)
[166] Wang Z S, Yang Y M, Wang Z M. Effects of sowing dates on leaf development characteristics of summer maize (*Zea mays* L.). Journal of Anhui Agricultural Sciences, 2014; 42(8): 2228–2232, 2236. (in Chinese)
[167] Wang Y Q, Zhang Y H, Li J P, Song W P, Deng W Y, Wang Z M. Grain filling and yield of summer maize under planting pattern of more plants per hill. Journal of Maize Sciences, 2015; 23(5): 117–123. (in Chinese).
[168] Kan Z R, Liu P, Li C, Qi J Y, Ma S T, Pu C, et al. Effects of biochar on soil water and growth of summer maize in the North China Plain. Journal of Maize Sciences, 2019; 27(1): 142–150. (in Chinese)
[169] Tong P Y. Study on physiological indexes of high yield summer maize. Beijing Agricultural Sciences, 1992; 5: 1–6. (in Chinese)
[170] Yan J, Cheng Y. Quantitative analysis and model studies of dynamic growth on summer-sowing maize Yedan 12. Journal of Hebei Agricultural Technology normal University, 1997; 4: 40–45. (in Chinese)
[171] Cao C, Li W, Dang H, Zheng C, Ma J, Li K. Study on the influences of plant densities on yield, yield traits and canopy photosynthesis characteristics of summer maize. Acta Agriculturae Boreali-Sinica, 2013; 28(S1): 161–166. (in Chinese)
[172] Cui X, Guo J, Liu X, Zhang X, Sun H. Effect of different planting patterns on radiation use efficiency and yield of summer maize. Acta Agriculturae Boreali-Sinica, 2013; 28(5): 231–238. (in Chinese)
[173] Wang Y, Tao H, Huang S, Xu L, Yang L, Qi L. Effects of nitrogen patterns on nitrogen use and yield benefit of summer maize. Journal of Nuclear Agricultural Sciences, 2013; 27(2): 219–224. (in Chinese)
[174] Shen X, Li J, Qu H, Wei F, Liu L, Meng J. Analysis on yield characters and adaptability of new summer maize variety in Taihe County. Chinese Agricultural Science Bulletin, 2009; 25(5): 155–157. (in Chinese)
[175] Chen L. Productivity and light and temperature conditions of different maize types in Beijing area. Geographical Research, 1987; 2: 95. (in Chinese)
[176] Tan C W, Huang Y D, Huang W J, Wang J H, Zhao C J, Liu L Y. Study on colony leaf area index of summer maize by remote sensing vegetation indexes method. Journal of Anhui Agricultural University, 2004; 31(4): 392–397. (in Chinese)
[177] Wang C L, Gong Y, Wang P. The analysis of main characteristic and yield of different types of summer maize. Journal of Maize Sciences, 2008; 16(2): 39–43. (in Chinese)
[178] Li R C, Tao H B, Zhang Z Q, Wang P, Liao S H. Study on measuring leaf area index of summer maize based on image processing technique. Journal of Anhui Agricultural Sciences, 2009; 37(26): 12871–12872. (in Chinese)
[179] Li R C, Tao H B, Zhang Z Q, Wang P, Liao S H. Study on summer maize group growth monitoring based on image processing technique. Journal of Maize Sciences, 2010; 18(2): 128–132. (in Chinese)
[180] Zhang L L, Wang P, Tao H B. Effects of nitrogen fertilizer supply way on growth and nitrogen use efficiency (NUE) in summer maize. Acta Agriculturae Boreali-Sinica, 2010; 25(S2): 177–181. (in Chinese)
[181] Xue Q Y, Wang J, Cao X P, Ma W, Feng L P. Effect of sowing date and variety on growth and population characteristics of summer maize in North China Plain. Journal of China Agricultural University, 2012; 17(5): 30–38. (in Chinese)
[182] Zhang L L, Wang P, Yang H, Fu J, Jing X. Effects on canopy building and photosynthesis traits of summer maize. Acta Agriculturae Boreali-Sinica, 2013; 28(S1): 332–336. (in Chinese)
[183] Qiu P C, Du Y C, Kong G D, Yu H R. Plant density and nitrogen amount affecting the yield of maize (‘Yidan52’ and ‘Yidan81’). Chinese Agricultural Science Bulletin, 2018; 34(1): 13–17. (in Chinese)
[184] Zhai L P, Liu W W, Cao G J. Dynamic study on the organism yield accumulation of corn in different yield treatments. Journal of Anhui Agricultural Sciences, 2010; 38(30): 16793–16795. (in Chinese)

[185] Chen Y X, Liu J, Chen X P, Zhang C C, Huang W, Tang Y Q, et al. Dry matter accumulation, yield and nitrogen use efficiency of crops rotation and intercropping systems in Sichuan. Journal of China Agricultural University, 2013; 18(6): 68–79. (in Chinese).
[186] Chen Y X, Chen X H, Tang Y Q, Zhang F S, Chen X P, Zhang C C, et al. Effect of nitrogen fertilizer on dry matter accumulation and yield in wheat /maize/soybean intercropping systems. Acta Prataculturae Sinica, 2014; 23(1): 73–83. (in Chinese)
[187] Ma Q R, Li S Z, Zhao H Q, Yang G X, Wu D Y, Dong W H. A study on accumulation and increment distribution of biomass of summer maize in Zhengzhou. Chinese Journal of Agrometeorology, 2007; 28(4): 430–432, 435. (in Chinese)
[188] Tong P Y, Ling B Y, Guan Y X. Dynamic simulation of dry matter accumulation in summer maize. Beijing Agricultural Sciences, 1996; 5: 22–25. (in Chinese).
[189] Li X L, Zhao M, Li C F, Ge J Z, Hou H P, Li Q, et al. Effect of sowing-date and planting density on dry matter accumulation dynamic and establishment of its simulated model in maize. Acta Agronomica Sinica, 2010; 36(12): 2143–2153. (in Chinese)
[190] Duan R, Jiang H. Agricultural meteorology. Beijing: China Meteorological Press, 2013; 176p.
[191] Chen H, Zhang X. Guide to agricultural meteorological service for maize production. Beijing: China Meteorological Press, 1999; 215p.
[192] Zhang J P, Sun J S, Liu Z G, Gao Y, Liu X F, Li X D. Effects of different mulching and soil moisture treatments on growth development and water consumption characteristics of summer maize. Water Saving Irrigation, 2008; 9: 13–17. (in Chinese)
[193] Liu Z G, Xiao J F, Sun J S, Zhang J P, Liu X F. Effects of soil moisture and mulches on the growth and the water use efficiency of summer maize. Journal of Maize Sciences, 2012; 20(3): 86–91. (in Chinese)
[194] Meng Y, Cai H J, Wang J, Zhang X P. Effect of straw mulching on the growth of summer maize and soil water utilization. Journal of Northwest Sci-Tech University of Agriculture and Forestry, 2005; 33(6): 131–135. (in Chinese)
[195] Hu W W, Zhao H J, Li H Q, Yuan L G, Zhao X J, Zheng J J. Effect of planting density on canopy photosynthesis of summer maize. Journal of Henan Agricultural Sciences, 2013; 42(1): 23–27. (in Chinese)
[196] Liu Y K, Yan X D, Xu Y P, Yue M Q. Effects of different tillage methods on soil moisture and growth and development of summer maize in coastal area. Tianjin Agricultural Sciences, 2014; 20(5): 84–87. (in Chinese)
[197] Xie Y H, Li L, Hong J P, Wang H T, Zhang L. Effects of nitrogen application and irrigation on grain yield, water and nitrogen utilizations of summer maize. Plant Nutrition and Fertilizer Science, 2012; 18(6): 1354–1361. (in Chinese)
[198] Lu D X, Xu Z H, Liu M, Liu P, Dong S T, Zhang J W, et al. Effect of vertically cutting roots at different horizontal distances from plant on leaf photosynthetic characteristics and yield of summer maize with different root types. Scientia Agricultura Sinica, 2017; 50(18): 3482–3493. (in Chinese)
[199] Wei W, Hu N, Hu W, Gu Y, Cao Y, Wu Y. Effect of sowing date on growth, development and yield of different maize varieties in Jilin Province. Journal of Maize Sciences, 2017; 25(6): 95–100. (in Chinese)
[200] Liu C X, Dong R, Zhang X Z, Liu T S, He C M, Wang L M, et al. Effects of different planting densities on leaf area index, dry matter accumulation and yield of maize. Shandong Agricultural Sciences, 2017; 49(2): 36–39. (in Chinese)
[201] Ding B H, Wu X M, Chen J L, Zhang X W, Yang J J, Zhao Z S. Effects of phosphorus fertilizer on the characteristics of dry matter accumulation and yield in maize under high planting density. Xinjiang Agricultural Sciences, 2017; 54(4): 675–681. (in Chinese)
[202] Liu Y, Wang L, Ni G H, Cong Z T. Spatial distribution characteristics of irrigation water requirement for main crops in China. Transactions of the CSAE, 2009; 25(12): 6–12. (in Chinese)
[203] Wang W, Cai H J, Wang J, Zhou B. Effects of water deficiency on plant height, chlorophyll relative content and yield of winter wheat. Journal of Irrigation and Drainage, 2009; 28(1): 41–44. (in Chinese)
[204] Shen X, Sun J, Liu Z, Zhang J, Liu X. Effect of the lower limit of irrigation control on the yield and quality of winter wheat. Transactions of the CSAE, 2010; 26(12): 58–65. (in Chinese)
[205] Yan Y J, Hao W P, Mei X R, Bai Q J, Liu L. Effects of water stress and rehydration on dry matter accumulation and water use efficiency in winter wheat at jointing stage. Chinese Journal of Agrometeorogy, 2011; 32(2): 190–195, 202. (in Chinese)
[206] Zhao Y M, Liu X Y, Zhong X L, Cao J F, Ren T S, Feng D H. Diagnosis of suitable soil layer and water threshold of winter wheat water deficit based on yield response. Transactions of the CSAE, 2014; 30(20): 147–154. (in Chinese)
[207] Meng Z J, Duan A W, Wang J L, Gao Y, Wang X S, Yang S J. Effect of regulated deficit irrigation on water evapotranspiration of winter wheat at different growth stages. Journal of Soil and Water Conservation, 2014; 28(1): 198–202. (in Chinese)
[208] Shi C X, Chen T, Feng F, Wang C J, Lyu X K, Zhang L, et al. Yield and soil water use efficiency of mixed winter wheat in Guanzhong irrigation area. Agricultural Research in the Arid Areas, 2017; 35(3): 29–37. (in Chinese)