RESEARCH ON SINGLE-PARAMETER LOGISTIC MODEL FOR RELATIVE PLANT HEIGHT AND RELATIVE DRY MATTER OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) AND SUMMER MAIZE (*ZEA MAYS* L.)

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Abstract. Logistic model has been widely used in simulating plant height and dry matter accumulation (DMA). However, the parameters of logistic model vary greatly under different crop cultivar, cultivation environment and weather conditions, which limits the application range of the model. In order to increase the applicability of the model, the maximum DMA, maximum plant height, and maximum growing degree days of typical crops were set to 1. Based on the method of normalization, the parameters a and b of the logistic model were estimated using a series of field trial data. The results showed that a/b values were a relatively stable constant due to a/b represented the peak of crop growth rate. Based on the above opinion, the single-parameter logistic models for plant height and DMA of typical food crops were established. The accuracy of the single-parameter models was evaluated, showing that the single-parameter models can accurately reflect the dynamic characteristics of plant height and DMA. These results can provide theoretical support for precise regulation and prediction of plant height and dry matter accumulation of two food crops.
Keywords: *growth function, relative growing degree days, food crops, crop modeling*

Introduction

Winter wheat and summer maize are the two main food crops cultivated worldwide. As one of the most important food production countries, China is the largest wheat and second-largest maize producer in the world (Liu et al., 2014a; Anjum et al., 2017), which in 2021 contributed 17.6% and 23.1% of global wheat and maize production respectively (FAO, 2023). With the rapid growth of global population, accurate analysis and forecast of food production have attracted increasing attention. Dry matter accumulation (DMA) and plant height are both important indicators to reflect the growth status and yield of food crops (Yin et al., 2011; Ning et al., 2013; Zhang et al., 2023; Gao et al., 2020). DMA determine the yield formation because the essence of crop DMA is the process of photosynthetic product formation (Ferrise et al., 2010; Ning et al., 2013). Plant height is the main agronomic index to characterize the stem

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morphology of crops, which is closely related to light absorption ability of the crop (Boomsma et al., 2010). Moreover, plant height is the basis of DMA, and is usually used by farmers to judge the growth state of crop (Kaplan et al., 2023). Compared with the data of DMA of crops, the data of plant height is easier to obtain. Recently, the importance of plant height to yield has been gradually recognized by researchers. Bendig et al. (2014) constructed the relationship between plant height and DMA, and used the plant height to estimate the DMA. Tao et al. (2020) estimated the yield of winter wheat using the spectral indices, ground-measured plant height, and plant height extracted from the hyperspectral remote sensing data, combined with three regression techniques. Gilliot et al. (2021) showed the potential of predicting maize yield based on the plant height extracted from unmanned aerial vehicle imagery. Ji et al. (2022) reported that the yield of faba bean can be reasonably estimated using the multiple time points data of plant height. Thus, it is necessary to study the dynamic changes in DMA and plant height for yield prediction.

At present, the simulation of dynamic changes of the DMA can usually be described in two ways: mechanism models and empirical models. The commonly used mechanism models include DSSAT, STICS and WOFOST models (Jones et al., 2003; Brisson et al., 2003; van Diepen et al., 1989). However, mechanism models have a lot of parameters and these parameters are difficult to determine. Instead, the empirical models are widely used because of the process of the parameter determination is relatively simple. The common empirical models used to describe crop growth including logistic, Gompertz and Richard equations (Verhulst, 1838; Gompertz, 1825; Richard, 1959). Among these models, logistic model is most frequently used in crop dynamic simulation because of its biological significance. Logistic model was originally proposed by ecologists to describe the laws of biological population growth and were subsequently widely used in DMA, plant height, leaf area expansion and grain filling (Hirooka et al., 2016; Liu et al., 2020; Bagheri et al., 2014; Sepaskhah et al., 2011).

As for the dynamic simulation of plant height, most crop mechanism growth models do not include simulations of plant height since they assume the canopy architecture as mono-layer or several layers to simulate light interception. The development of plant height model is slow over the past decades (Confalonieri et al., 2011). At present, using a logistic model is the most common method for simulating the change characteristics of plant height.

Many investigators have applied logistic models to simulate the growth processes of DMA and plant height. Wardhani and Kusumastuti (2014) described the height growth of maize using logistic and Gompertz models with the days after planting as independent variables respectively. Ma et al. (2013) used logistic model to simulate the plant height, leaf area index (LAI), and DMA of spring wheat under different irrigation regimes. And a modified logistic model was established to simulate DMA and LAI based on plant height. Considering the effect of different environmental conditions and plating dates, some studies have shown that growing degree days (GDD) can be used instead of days after planting in the logistic function (Shabani et al., 2018; Mahbod et al., 2014; Sepaskhah et al., 2011). Mahbod et al. (2014) used logistic models to predict DMA and grain yield of winter wheat in semi-arid regions based on GDD. Bagheri et al. (2014) simulated maize daily DMA using logistic model for different water and nitrogen management regimes. Wang et al. (2014) presented a logistic model calculating winter wheat above-ground biomass and LAI for different irrigation treatments. Liu et al. (2020) established a universal logistic model simulating DMA and

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plant height of winter wheat in China using GDD as independent variable. Wang et al. (2021) and Guo et al. (2022) developed a universal logistic model predicting the plant height of cotton and summer maize in different regions. However, the parameters of logistic function vary greatly under different crop cultivar, cultivation environment and weather conditions. The difference of logistic model parameters in different environments limits the popularization and application of the model. In addition, there is still a lack of in-depth analysis of the changing characteristics of the parameters of the logistic model and the relationship between the parameters.

In this paper, the variations of relative plant height (RH) and relative dry matter accumulation (RDMA) with the relative growing degree days (RGDD) were investigated to clarify the relationship between the parameters of the normalized logistic model. Thus, the objective of this study was to establish and evaluate a normalized logistic model for simulating plant height and DMA in winter wheat and summer maize with reduced complexity and less parameter.

Materials and methods

Data collection

The data of crop plant height and DMA are obtained from literature published on China National Knowledge Infrastructure (https://www.cnki.net/). The growth characteristics data were directly from the tables and text or indirectly from figures using Get Data Graph Digitizer software. The selected literature meets the following criteria: (1) Data collection is restricted to field experiment studies, (2) The growth data under the condition of widely used agronomic technologies were taken into consideration, and data from some new technologies were removed. Based on above criteria, 20 articles and 13 articles were selected to analyze growth characteristics of DMA and plant height of typical food crops, respectively. Detailed information on the literature is listed in *Tables 1–4*.

The meteorological data are obtained from the China Meteorological Data Network (http://data.cma.cn), including the daily maximum temperature and the daily minimum temperature during the crop growth period. GDD is the difference between the average daily temperature and the minimum temperature required for crop activity, as shown below (McMaster and Wilhelm, 1997):

$$GDD = \sum (T_{avg} - T_{base}) \quad \text{(Eq.1)}$$

T_{avg} is average daily temperature; T_{base} is minimum temperature required for crop activity. T_{avg} is calculated as follows:

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

T_x is daily maximum temperature; T_n is daily minimum temperature; T_{upper} is the maximum temperature required for crop activities.

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Table 1. *Data sources of winter wheat dry matter accumulation*

Location	Year	Sample size	References	Purpose
Qingyang City, Gansu Province	1995-1996	1	Zhang et al. (2004)	Model establishment
Taiyuan City, Shanxi Province	2014-2015	4	Shi et al. (2017)	
Jinzhong City, Shanxi Province	2015-2016	1	Tian et al. (2012)	
Yangling City, Shaanxi Province	2012-2013	2	Yang et al. (2015)	
Hefei City, Anhui Province	2010-2011	1	Teng (2012)	
Zhengzhou City, Henan Province	2009-2010	1	Liu et al. (2012)	
Haozhou City, Anhui Province	2010-2011	2	Zhang et al. (2014)	Model validation
Gaoyou City, Jiangsu Province	2001-2002	1	Huang et al. (2008)	
Handan City, Hebei Province	2011-2012	2	Liu et al. (2014b)	

Table 2. *Data sources of summer maize dry matter accumulation*

Location	Year	Sample size	References	Purpose
Beijing City	1980	1	Chen (1986)	Model establishment
Shijiazhuang City, Hebei Province	2010	1	Wang et al. (2013)	
Taian City, Shandong Province	2011	1	Feng et al. (2015)	
Zhengzhou City, Henan Province	1994	1	Ma et al. (2007)	
Songyuan City, Jilin Province	2014	1	Sun et al. (2017)	
Luoyang City, Henan Province	2013	2	Jin et al. (2014)	
Cangzhou City, Hebei Province	2016	2	Kan et al. (2019)	
Yangling City, Shaanxi Province	2008	1	Ma et al. (2010)	
Lang fang City, Hebei Province	2009	1	Li et al. (2010)	Model validation
Luoyang City, Henan Province	2012	2	Liang et al. (2013)	
Taian City, Shandong Province	2015	2	Zhang et al. (2017)	

Table 3. *Data sources of winter wheat plant height*

Location	Year	Sample size	References	Purpose
Nanjing City, Jingsu Province	2013-2014	1	Dong et al. (2017)	Model establishment
Beijing City	2004-2005	2	Kong et al. (2008)	
Langfang City, Hebei Province	2013-2014	3	Jiao et al. (2017)	
XinXiang City, Henan Province	2009-2010	2	Gao et al. (2012)	
YunCheng City, Shanxi Province	2012-2013	2	Ding et al. (2014)	
Cangzhou City, Hebei Province	2010-2011	2	Wu and Wang (2009)	Model validation
Yangling City, Shannxi Province	2001-2002	3	Liu et al. (2010)	

Table 4. *Data sources of summer maize plant height*

Location	Year	Sample size	References	Purpose
Cangzhou City, Hebei Province	2013	2	Liu et al. (2014c)	Model establishment
Tianchang City, Anhui Province	2009	3	Xiao et al. (2010)	
Xinxiang City, Henan Province	2007	2	Zhang et al. (2008)	
jiamusi City, Heilongjiang Province	2014	3	Zhu et al. (2015)	
Yiyang City, Henan Province	1999	3	Fu et al. (2005)	Model validation
Xinxiang City, Henan Province	2009	2	Xiao et al. (2011)	

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Data normalization

The maximum value of DMA and plant height were set to 1, respectively. The data of plant height and DMA were normalized. The RDMA, RH and RGDD were all in the range of [0-1].

$$RDMA_i = \frac{DMA_i}{DMA_{max}} \quad \text{(Eq.3)}$$

$$RH_i = \frac{H_i}{H_{max}} \quad \text{(Eq.4)}$$

$$RGDD_i = \frac{GDD_i}{GDD_{max}} \quad \text{(Eq.5)}$$

DMA_i is measured dry matter accumulation, $DMA_{\max}$ is maximum dry matter accumulation, H_i is measured plant height, $H_{\max}$ is maximum plant height, GDD_i is growing degree days from sowing to measurement period, $GDD_{\max}$ is growing degree days when crop is mature.

Statistical analysis

The determination coefficient (R^2) and the root mean square error (RMSE) were used to evaluate the accuracy of the model. These statistical indexes could be calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad \text{(Eq.6)}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O_i}\right)^2} \quad \text{(Eq.7)}$$

where O_i is measured value, P_i is the simulated value, $\overline{O_i}$ is the average value of measured data, and n is the number of observations.

Single-parameter logistic model construction

Normalized logistic model

The formula of the logistic growth function is as follows:

$$y = \frac{y_{max}}{1 + e^{a-bt}} \quad \text{(Eq.8)}$$

where y is growth index (plant height or DMA), $y_{\max}$ is the upper limit of the crop growth index, t is the number of days after planting or sowing, a and b are coefficients of the equation.

Some researchers suggested that applying logistic model to simulate crop growth status under different weather conditions, it is more reasonable to use GDD instead of

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calendar days after planting (Mahbod et al., 2014; Sepaskhah et al., 2011). Thus, logistic model can be expressed as follows:

$$y = \frac{y_{max}}{1 + e^{a-bGDD}} \quad \text{(Eq.9)}$$

In order to eliminate the differences in crop growth characteristics caused by different crop varieties, soil types and management methods, the plant height and DMA were normalized (Fu et al., 2009). The normalized logistic model is as follows:

$$Ry = \frac{y}{y_{max}} = \frac{1}{1 + e^{a-bRGDD}} \quad \text{(Eq.10)}$$

Characteristic parameters of the normalized logistic equation

The instantaneous rate of relative dry matter accumulation or relative plant height at the moment of RGDD was obtained by taking derivative of *Equation 10:*

$$Ry' = \frac{be^{a-bRGDD}}{(1 + e^{a-bRGDD})^2} \quad \text{(Eq.11)}$$

In order to determine the maximum rate and its corresponding RGDD, the second derivative of normalized logistic equation is as follows:

$$Ry'' = \frac{b^2(e^{a-bRGDD} - 1)e^{a-bRGDD}}{(1 + e^{a-bRGDD})^3} \quad \text{(Eq.12)}$$

Let *Ry*” = 0, an inflection point (a/b, b/4) was defined. b/4 and a/b are respectively the maximum rate and its corresponding RGDD.

Relationships between parameters of normalized logistic model

The parameters of the normalized logistic model were estimated using data set for model establishment in MATLAB software. *Tables 5* and *6* show severally the values of parameters a and b of normalized logistic model describing the DMA of winter wheat and summer maize. And *Tables 7* and *8* show severally the values of parameters a and b of normalized logistic model describing plant height dynamic process of winter wheat and summer maize. It can be seen that that a/b values of different crops were relatively stable constants. From the above analyses, we can know that when RGDD = a/b, the growth rate reaches maximum. Combined with the RGDD when the maximum growth rate occurs, the single-parameter logistic models of plant height or DMA were established.

Table 5 shows that a_1/b_1 ranges from 0.531 to 0.591. Since the variation amplitude of a_1/b_1 values are small, in order to simplify the model, take the average value. Therefore, the normalized DMA logistic model of winter wheat can be modified as follows:

$$RDMA_{wheat} = \frac{1}{1 + e^{0.559b_1 - b_1 RGDD}} \quad \text{(Eq.13)}$$

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Table 6 shows that a_2/b_2 ranges from 0.538 to 0.622. Similarly, take the average of a_2/b_2. The normalized DMA logistic model of summer maize can be modified as follows:

$$RDMA_{maize} = \frac{1}{1 + e^{0.579\,b_2 - b_2 RGDD}} \quad \text{(Eq.14)}$$

Table 7 shows that a_3/b_3 ranges from 0.344 to 0.449. Similarly, take the average of a_3/b_3. The normalized plant height logistic model of winter wheat can be modified as follows:

$$RH_{wheat} = \frac{1}{1 + e^{0.393\,b_3 - b_3 RGDD}} \quad \text{(Eq.15)}$$

Table 8 shows that a_4/b_4 ranges from 0.361 to 0.436. Similarly, take the average of a_4/b_4. The normalized plant height logistic model of summer maize can be modified as follows:

$$RH_{maize} = \frac{1}{1 + e^{0.391\,b_4 - b_4 RGDD}} \quad \text{(Eq.16)}$$

Table 5. *Parameter fitting results of normalized logistic model for relative winter wheat DMA*

Dataset	a_1	b_1	R^2	RMSE	a_1/b_1
1	7.831	14.17	0.99	0.02	0.553
2	3.650	6.608	0.99	0.03	0.552
3	3.694	6.473	0.98	0.04	0.571
4	3.567	6.514	0.99	0.04	0.548
5	3.94	7.002	0.98	0.06	0.563
6	5.133	8.676	0.98	0.06	0.592
7	4.362	7.918	0.99	0.02	0.551
8	4.238	7.752	0.99	0.04	0.547
9	4.001	7.530	0.99	0.03	0.531
10	5.187	8.896	0.99	0.03	0.583
Average					0.559

Table 6. *Parameter fitting results of normalized logistic model for relative summer maize DMA*

Dataset	a_2	b_2	R^2	RMSE	a_2/b_2
1	4.688	7.594	0.99	0.05	0.617
2	3.915	7.103	0.99	0.04	0.551
3	4.760	7.650	0.98	0.04	0.622
4	4.198	7.581	0.99	0.05	0.554
5	4.564	7.980	0.99	0.03	0.572
6	3.808	6.564	0.99	0.04	0.580
7	3.754	6.404	0.99	0.04	0.586
8	4.115	7.415	0.99	0.03	0.555
9	4.375	8.126	0.98	0.04	0.538
10	4.065	6.607	0.94	0.09	0.615
Average					0.579

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Table 7. *Parameter fitting results of normalized logistic model for relative winter wheat plant height*

Dataset	a_3	b_3	R^2	RMSE	a_3/b_3
1	8.688	19.33	0.98	0.01663	0.450
2	4.833	12.32	0.99	0.00625	0.392
3	4.349	10.51	0.99	0.01387	0.414
4	3.357	9.748	0.99	0.04604	0.344
5	3.772	9.686	0.98	0.06795	0.389
6	3.228	8.916	0.98	0.06445	0.362
7	2.846	6.637	0.97	0.04937	0.429
8	3.426	8.402	0.99	0.04102	0.408
9	2.704	7.279	0.99	0.00894	0.372
10	2.337	6.353	0.99	0.01375	0.368
Average					0.393

Table 8. *Parameter fitting results of normalized logistic model for summer relative maize plant height*

Dataset	a_4	b_4	R^2	RMSE	a_4/b_4
1	2.712	7.154	0.96	0.09664	0.379
2	2.688	7.427	0.98	0.07587	0.362
3	4.073	10.78	0.99	0.01804	0.378
4	3.914	9.437	0.98	0.05325	0.415
5	3.768	8.976	0.99	0.03806	0.420
6	3.231	8.569	0.99	0.02085	0.377
7	3.640	8.340	0.98	0.03444	0.436
8	2.371	6.447	0.99	0.03298	0.368
9	2.248	6.025	0.97	0.05004	0.373
10	2.404	5.938	0.98	0.04032	0.405
Average					0.391

Model evaluation

Evaluation of single-parameter DMA model with data for model establishment

In order to evaluate the established single-parameter logistic model, *Equations 16* and *17* were used to fit the parameters of the two crops respectively. Then predicted RGDD value of the two crops were calculated. The comparison results with the measured data are shown in *Figure 1*. It can be seen that the established single-parameter models reasonably describe the RGDD process of two crops. The measured and predicted values were plotted 1: 1 line to verify the simulation performance of the model in *Figure 2*. It can be seen that the scattered points are evenly distributed around the 1:1 line. The value of R^2 and RMSE are 0.98 and 0.05. Therefore, the single-parameter logistic models had a satisfactory precise simulating the RDMA of two crops.

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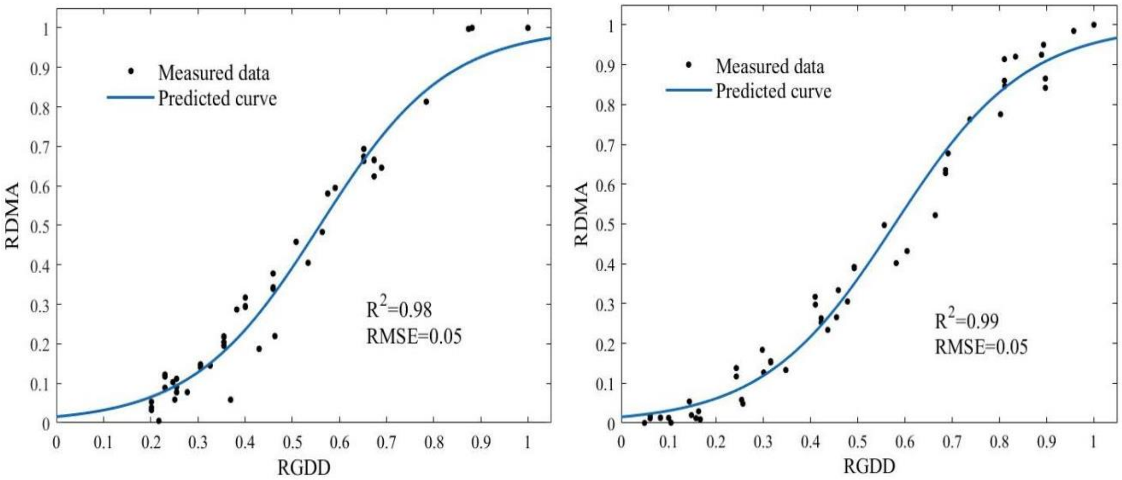
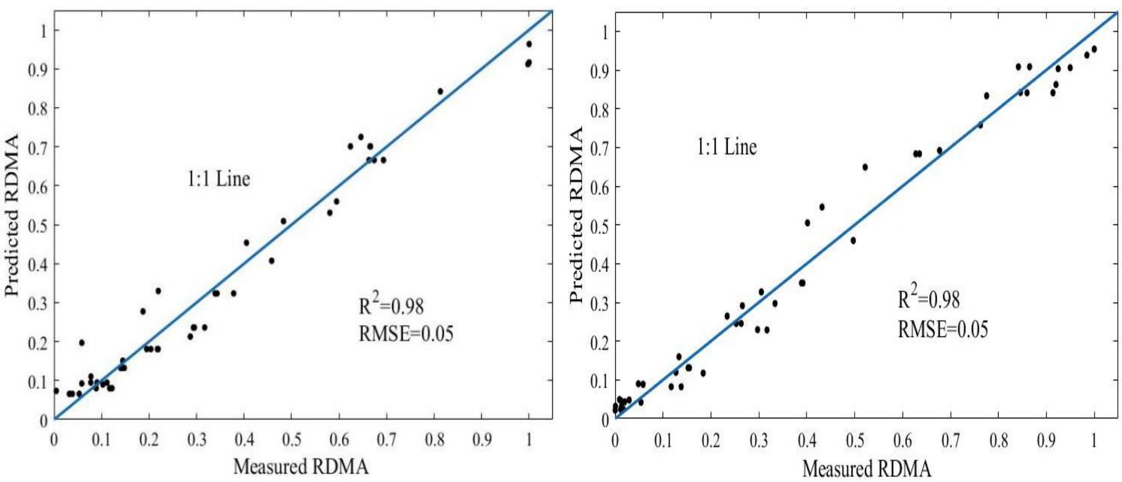


(a) Winter wheat (b) Summer maize

Figure 1. *Measured and predicted relative dry matter accumulation based on the single-parameter logistic model for winter wheat and summer maize (data for model establishment)*



(a) Winter wheat (b) Summer maize

Figure 2. *Relationship between measured and predicted values of relative dry matter accumulation for winter wheat and summer maize (data for model establishment)*

Evaluation of single-parameter DMA model with data for model validation

In order to further evaluate the performance of the single-parameter logistic model, 5 added dry matter data provided by the relevant literature were used to validate the model. The predicted and measured variation curves of RDMA in two crops are shown in *Figure 3*. Results indicate that the simulation effect of the simplified logistic model is acceptable. Then the measured and predicted wheat winter and summer maize RDMA by developed simplified logistic model was compared with 1:1 line in *Figure 4*. The values of R^2 (0.97 and 0.98) and RMSE (0.06 and 0.04) showed that single-parameter logistic model predicted winter wheat and summer maize with good accuracy. Therefore, the simplified model can be used to simulate the RDMA with the RGDD.

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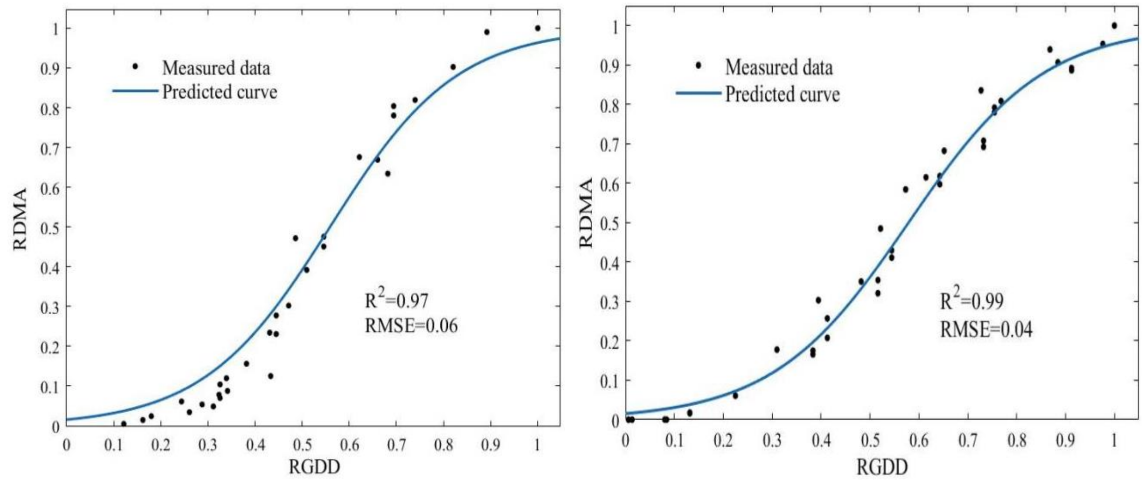
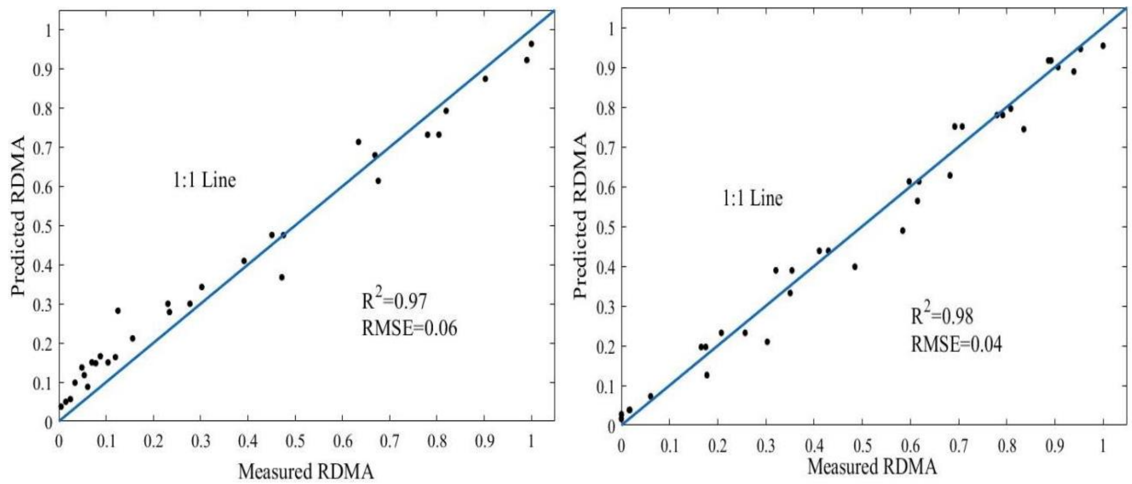


(a) Winter wheat (b) Summer maize

Figure 3. *Measured and predicted relative dry matter accumulation based on the single-parameter logistic model for winter wheat and summer maize (data for model validation)*



(a) Winter wheat (b) Summer maize

Figure 4. *Relationship between measured and predicted values of relative dry matter accumulation for winter wheat and summer maize (data for model validation)*

Evaluation of single-parameter plant height model with data for model establishment

Equations 18 and *19* were used to fit the parameters of the two crops, and then predicted RH values were calculated bases on the established single-parameter logistic model. The predicted and measured values of RH are shown in *Figure 5*. It can be seen from *Figure 5* that the established single-parameter model precisely describes the RH change process of the two crops of winter wheat and summer maize. To further evaluate the results of singe parameter logistic model for RH prediction, all values of predicted and measured RH were compared in *Figure 6*. The statistical parameters R^2 (0.96 and 0.97) and RMSE (0.06 and 0.05) showed acceptable estimation of RH.

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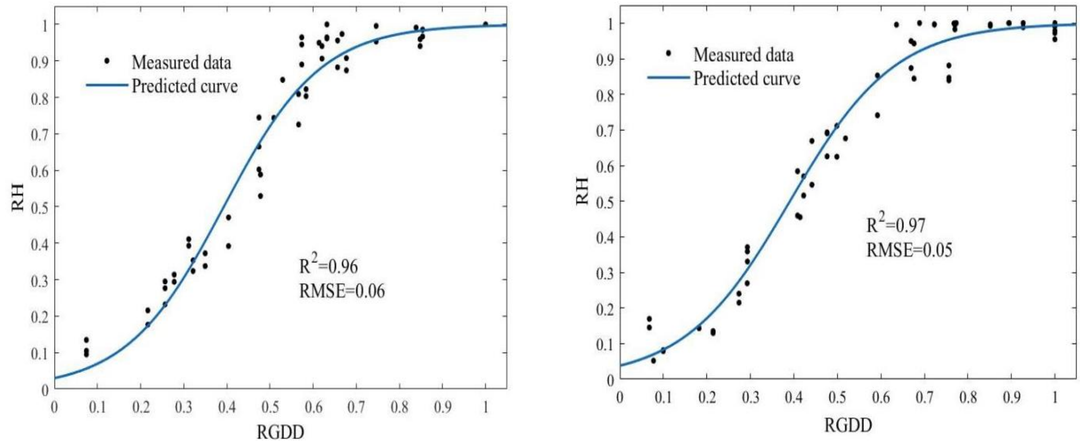
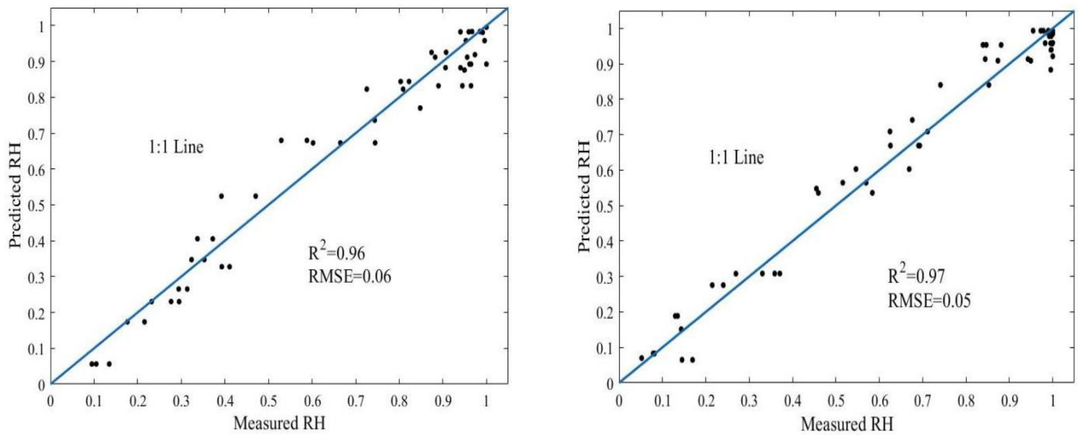
Evaluation of single-parameter plant height model with data for model validation

5 other plant height data provided by the relevant literature were used to validate the model. The predicted and predicted RH are shown in *Figure 7*. Agreement between measured and predicted values of RH was obtained with good accuracy. In order to further evaluate the performance single-parameter plant height logistic model, the measured and simulated winter wheat was compared with 1:1 line in *Figure 8*. The values of R^2 (0.95 and 0.91) and RMSE (0.06 and 0.08) showed that single-parameter logistic model predicted winter wheat and summer maize RH with good accuracy. Therefore, the normalized logistic model was validated with good accuracy.



(a) Winter wheat (b) Summer maize

Figure 5. *Measured and predicted relative plant height based on the single-parameter logistic model for winter wheat and summer maize (data for model establishment)*



(a) Winter wheat (b) Summer maize

Figure 6. *Relationship between measured and predicted values of relative plant height for winter wheat and summer maize (data for model establishment)*

Discussion

Plant height and DMA are important indicators reflecting crop yield formation (Jiang et al., 2020; Rebetzke et al., 2011; Arduini et al., 2006; Fang et al., 2010). Quantitative

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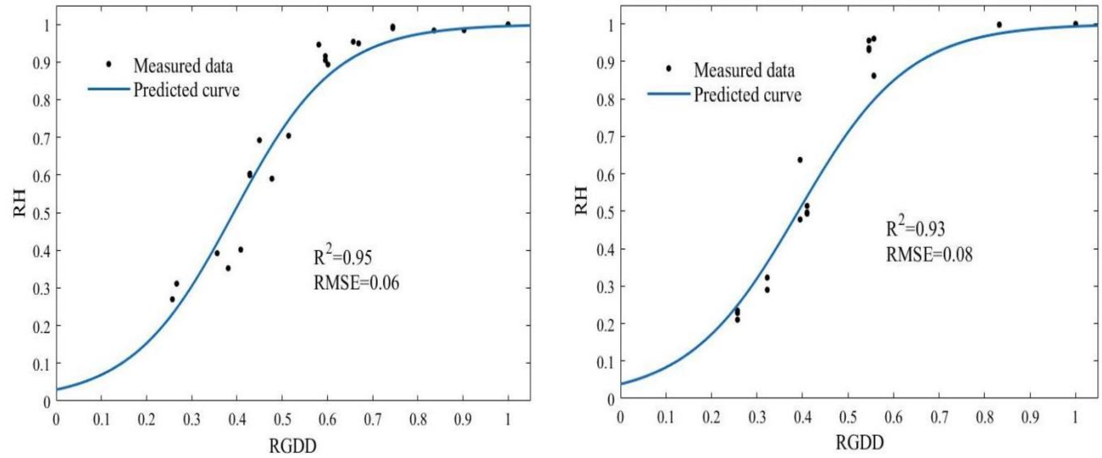
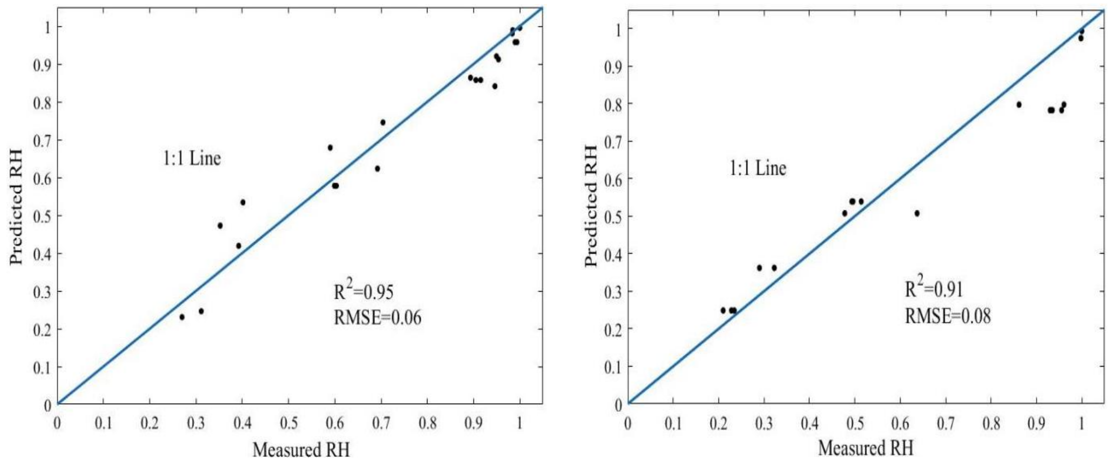
analysis of the dynamic changes of crop plant height and DMA is the key to deepening understanding of crop field management. Because of its biological significance and good simulation effect, the logistic model is used by many scholars to simulate the dynamic changes of plant height and DMA in winter wheat and summer maize (Sepaskhah et al., 2011; Mahbod et al., 2014; Liu et al., 2020). For example, Mahbod et al. (2014) developed an empirical logistic model for winter wheat in semiarid region. Result showed that the model can be applicable in different years and location in this study region. Liu et al. (2020) established a universal logistic model simulating the characteristics of plant height and DMA and of winter wheat in China based on growing degree days. Similarly, the logistic model was used to estimate DMA and grain yield of maize with an acceptable accuracy at different irrigation water and nitrogen levels (Bagheri et al., 2014; Sepaskhah et al., 2011). However, the parameter of logistic model under different varieties, cultivation measures and meteorological conditions has large differences, which restricts the applicability of model (Fu et al., 2009).



(a) Winter wheat (b) Summer maize

Figure 7. *Measured and predicted relative plant height based on the single-parameter logistic model for winter wheat and summer maize (data for model validation)*



(a) Winter wheat (b) Summer maize

Figure 8. *Relationship between measured and predicted values of relative plant height for winter wheat and summer maize (data for model validation)*

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In this study, a normalized logistic equation was used to construct a dynamic universal model of RH and RDMA in winter wheat and summer maize, which avoided differences due to different varieties, planting dates, planting densities, and farming practices. In the process of fitting parameters using a normalized logistic model, it was found that the value of a/b is a relatively stable constant. Subsequently, the logistic model can be simplified to a single-parameter model. The performance of the single-parameter logistic models was evaluated a lot of field data. Statistic indexes showed that single-parameter can accurately reflect the changes in plant height and DMA of winter wheat and summer maize during the growth period. Moreover, the simplified model has only one parameter, which is easier to popularize and apply than the traditional logistic model. Generally, the maximum GDD of a given cultivar of crop was stable in a certain region. The normalized model could characterize plant height and DMA growth dynamic of crops when maximum plant height, maximum DMA, and parameter b were obtained (Fu et al., 2009). The corresponding dry matter and plant height values can be obtained by substituting the RGDD into the equation.

In this study, the relationship between parameters a and b is a basic condition for establishing a single-parameter logistic model. This condition is obtained based on the normalized logistic model, and this study only includes winter wheat and summer maize. For other crops, it is still necessary to study the normalized logistic model, and then establish the corresponding simplified model. The RGDD used in this study can also represent the relative growth period of crops. Therefore, the relationship between the relative growth period of crops and growth indicators still needs to be further studied to clarify the internal relationship between their corresponding model parameters. In general, this study has certain reference significance for establishing a simplified logistic model for other crops.

Conclusion

This paper normalizes the GDD, DMA, and plant height data of two major food crops. In the process of fitting parameters using a normalized logistic model, it was found that the a/b value is a relatively stable constant. Based on this opinion, single-parameter models of several crops were established. These parameters can provide theoretical support for precise regulation of crop plant height and DMA. It is concluded that single-parameter logistic models are appropriate for accurate prediction of DMA and plant height of typical food crops.

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REFERENCES

[1] Anjum, S. A., Tanveer, M., Hussain, S., Ashraf, U., Khan, I., Wang, L. (2017): Alteration in growth, leaf gas exchange, and photosynthetic pigments of maize plants under combined cadmium and arsenic stress. – Water, Air, & Soil Pollution 228(1): 1-12.

[2] Arduini, I., Masoni, A., Ercoli, L., Mariotti, M. (2006): Grain yield, and dry matter and nitrogen accumulation and remobilization in durum wheat as affected by variety and seeding rate. – European Journal of Agronomy 25(4): 309-318.
[3] Bagheri, S., Sepaskhah, A. R., Razzaghi, F., Zand-Parsa, S. (2014): Developing a dynamic yield and growth model for maize under various water and nitrogen regimes. – Archives of Agronomy and Soil Science 60(9): 1173-1191.
[4] Bendig, J., Bolten, A., Bennertz, S., Broscheit, J., Eichfuss, S., Bareth, G. (2014): Estimating biomass of barley using crop surface models (CSMs) derived from UAV-based RGB imaging. – Remote Sensing 6(11): 10395-10412.
[5] Boomsma, C. R., Santini, J. B., West, T. D., Brewer, J. C., McIntyre, L. M., Vyn, T. J. (2010): Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment. – Soil and Tillage Research 106(2): 227-240.
[6] Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Sinoquet, H. (2003): An overview of the crop model STICS. – European Journal of Agronomy 18(3-4): 309-332.
[7] Chen, L. (1986): The effects of temperature and radiation on productivity of different patterns corn in Beijing district. – Acta Agriculturae Universitatis Pekinensis 12(4): 409-415 (in Chinese with English abstract).
[8] Confalonieri, R., Bregaglio, S., Rosenmund, A. S., Acutis, M., Savin, I. (2011): A model for simulating the height of rice plants. – European Journal of Agronomy 34(1): 20-25.
[9] Ding, J. J., Li, L., Wang, X. Y. (2014): Effects of water and fertilizer coupling on growth and yield of winter wheat. – Soil and Water Conservation Science and Technology in Shanxi 4: 14-16 (in Chinese with English abstract).
[10] Ding, D., Feng, H., Zhao, Y., Hill, R. L., Yan, H., Chen, H., Zhang, T. (2019): Effects of continuous plastic mulching on crop growth in a winter wheat-summer maize rotation system on the Loess Plateau of China. – Agricultural and Forest Meteorology 271: 385-397.
[11] Dong, J. M., Shi, D. W., Liu, R. X., Ma, C. C. (2017): Effects of simulated warming and no tillage on growth of winter wheat. – Hubei Agricultural Sciences 56(23): 79-84 (in Chinese with English abstract).
[12] Fang, Y., Xu, B. C., Turner, N. C., Li, F. M. (2010): Grain yield, dry matter accumulation and remobilization, and root respiration in winter wheat as affected by seeding rate and root pruning. – European Journal of Agronomy 33(4): 257-266.
[13] FAO (2023): Crop Prospects and Food Situation – Quarterly Global Report No. 1, March 2023. FAO, Rome.
[14] Feng, S., Wang, S., Peng, M., Liu, N., Zhao, G. (2015): Effects of different planting densities on grain yield, LAI and dry matter accumulation of summer maize. – Acta Agriculturae Jiangxi 27(3): 1-22 (in Chinese with English abstract).
[15] Ferrise, R., Triossi, A., Stratonovitch, P., Bindi, M., Martre, P. (2010): Sowing date and nitrogen fertilisation effects on dry matter and nitrogen dynamics for durum wheat: an experimental and simulation study. – Field Crops Research 117(2-3): 245-257.
[16] Fu, G., Wang, J., Li, C., Liu, S., Zhao, Y., Jiao, N. (2005): Effects of stubble mulching and tillage management on growth and grain yield in summer maize. – Journal of Henan Agricultural Sciences 3: 23-26 (in Chinese with English abstract).
[17] Fu, X. L., Zhao, M., A. O., Zhou, B. Y., Cui, G. M., Ding, S. Z. (2009): Optimal model for dynamic characteristics of grain weight commonly used in wheat and maize. – Acta Agronomica Sinica 35(2): 309-316.
[18] Gao, Y., Qiu, X. Q., Gong, W. J., Duan, A. J., Wang, J. L., Meng, Z. J., Sun, J. S. (2012): Effects of soil moisture before sowing on growth and yield of winter wheat. – Journal of Irrigation and Drainage 31(3): 17-20 (in Chinese with English abstract).

[19] Gao, Z., Wang, Y., Tian, G., Zhao, Y., Li, C., Cao, Q., He, M. (2020): Plant height and its relationship with yield in wheat under different irrigation regime. – Irrigation Science 38(4): 365-371.
[20] Gilliot, J. M., Michelin, J., Hadjard, D., Houot, S. (2021): An accurate method for predicting spatial variability of maize yield from UAV-based plant height estimation: a tool for monitoring agronomic field experiments. – Precision Agriculture 22(3): 897-921.
[21] Gompertz, B. (1825): On the nature of the function expressive of the law of human mortality, and on a new method of determining the value of life contingencies. – Proceedings of the Royal Society of London (115): 513-583.
[22] Guo, Y., Liu, Y., Wang, Q., Su, L., Zhang, J., Wei, K. (2022): Regional growth model for summer maize based on a logistic model: case study in China. – International Journal of Agricultural and Biological Engineering 15(5): 41-55.
[23] Hirooka, Y., Homma, K., Shiraiwa, T., Kuwada, M. (2016): Parameterization of leaf growth in rice (*Oryza sativa* L.) utilizing a plant canopy analyzer. – Field crops research 186: 117-123.
[24] Huang, Y., Fan, Y., Li, B., Dai, X., Zhang, H., Xu, K. (2008): Effects of nitrogen application strategies on population structure and grain yield of the weak-gluten wheat Ningmai 9. – Chinese Agricultural Science Bulletin 24(9): 122-126 (in Chinese with English abstract).
[25] Ji, Y., Chen, Z., Cheng, Q., Liu, R., Li, M., Yan, X., Yang, T. (2022): Estimation of plant height and yield based on UAV imagery in faba bean (Vicia faba L.). – Plant Methods 18(1): 1-13.
[26] Jiang, T., Liu, J., Gao, Y., Sun, Z., Chen, S., Yao, N., He, J. (2020): Simulation of plant height of winter wheat under soil water stress using modified growth functions. – Agricultural Water Management 232: 106066.
[27] Jiao, Y. P., Wang, F. T., Wu, J., Li, X. X., Tan, H. B. (2017): Effects of drip irrigation and micro-sprinkler irrigation of hoses on growth and yield of winter wheat. – Journal of Hebei Agricultural Science 21(6): 17-22 (in Chinese with English abstract).
[28] Jin, S., Li, L., Wan, H., Cai, S., Wei, Y., Zhao, H. (2014): Study on physiological indexes of colony of new maize variety Luoyu 818. – Acta Agriculturae Jiangxi 26(6): 11-14 (in Chinese with English abstract).
[29] Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Ritchie, J. T. (2003): The DSSAT cropping system model. – European Journal of Agronomy 18(3-4): 235-265.
[30] Kan, Z. R., Liu, P., Li, C., Qi, J. Y., Ma, S. T., Pu, C., Zhao, X., Zhang, H. L. (2019): Effects of biochar on soil water and growth of summer corn in the North China Plain. – Journal of Maize Sciences 27(1): 146-154 (in Chinese with English abstract).
[31] Kaplan, G., Fine, L., Lukyanov, V., Malachy, N., Tanny, J., Rozenstein, O. (2023): Using Sentinel-1 and Sentinel-2 imagery for estimating cotton crop coefficient, height, and leaf area index. – Agricultural Water Management 276: 108056.
[32] Kong, K., Yun, Y., Duan, Y., Lu, W. L., Xu, H. Y. (2008): Field experiment on growth and yields of winter wheat under different water and nitrogen treatments. – Transactions of the Chinese Society of Agricultural Engineering 24(12): 36-40 (in Chinese with English abstract).
[33] Li, X., Zhao, M., Li, C., Ge, J., Hou, H., Li, Q., Hou, L. (2010): Effect of sowing-date and planting density on dry matter accumulation dynamic and establishment of its simulated model in maize. – Acta Agronomica Sinica 36(12): 2143-2153 (in Chinese with English abstract).
[34] Liang, X. W., Zhao, B. X., Wan, H. L., Lei, X. B., Chen, R. L., Zhao, H. L. (2013): Study on group dynamic indexes of 'Luoyu 863' of maize. – Chinese Agricultural Science Bulletin 29(36): 96-101 (in Chinese with English abstract).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_25392556

[35] Liu, P., Cai, H., Wang, J. (2010): Effects of soil water stress on growth development, dry-matter partition and yield constitution of winter wheat. – Research of Agricultural Modernization 31(3): 330-333 (in Chinese with English abstract).
[36] Liu, J., Xiong, S. P., Yang, Y., Zhai, Q., Wang, Y., Wang, J., Ma, X. (2012): A model to predict dry matter accumulation dynamics in wheat based on the normalized method. – Acta Ecologica Sinica 32(17): 5512-5520 (in Chinese with English abstract).
[37] Liu, B., Liu, L., Tian, L., Cao, W., Zhu, Y., Asseng, S. (2014a): Post-heading heat stress and yield impact in winter wheat of China. – Global Change Biology 20(2): 372-381.
[38] Liu, B. H., Su, Y. H., Wang, X. X., Zhang, G. Z., Chen, D. M., Ma, Y. A., Li, Y. M. (2014b): Effects of planting density on the main agronomic traits and yield of winter wheat Hanmai No. 13. – Journal of Hebei Agricultural Sciences 18(2): 13-17 (in Chinese with English abstract).
[39] Liu, Y. K., Xian, X. D., Xu, Y. P., Yue, M. Q. (2014c): Effects of different tillage methods on soil moisture and growth and development of summer maize in coastal area. – Tianjin Agricultural Sciences 5: 88-91 (in Chinese with English abstract).
[40] Liu, Y., Su, L., Wang, Q., Zhang, J., Shan, Y., Deng, M. (2020): Comprehensive and quantitative analysis of growth characteristics of winter wheat in China based on growing degree days. – Advances in Agronomy 159: 237-273.
[41] Ma, Q. R., Li, S. Z., Zhao, H. Q., Yang, G. X., Wu, D. Y., Dong, W. H. (2007): A study on accumulation and increment distribution of biomass of summer maize in Zhengzhou. – Chinese Journal of Agrometeorology 28(4): 430-432 (in Chinese with English abstract).
[42] Ma, Y. H., Xue, J. Q., Zhang, R. H. (2010): Relationship between dry matter accumulation and distribution to yield of different maize cultivars. – Guangdong Agricultural Sciences 37(3): 36-40 (in Chinese with English abstract).
[43] Ma, L., Wang, Q., Fan, J. (2013): Characteristics and models of spring wheat growth by a modified logistic model in the desert oasis conditions. – Journal of Food, Agriculture and Environment 11(1): 614-624.
[44] Mahbod, M., Sepaskhah, A. R., Zand-Parsa, S. (2014): Estimation of yield and dry matter of winter wheat using logistic model under different irrigation water regimes and nitrogen application rates. – Archives of Agronomy and Soil Science 60(12): 1661-1676.
[45] McMaster, G. S., Wilhelm, W. (1997): Growing degree-days: one equation, two interpretations. – Agricultural and Forest Meteorology 87(4): 291-300.
[46] Mohanty, M., Painuli, D. K., Misra, A. K., Bandyopadhyaya, K. K., Ghosh, P. K. (2006): Estimating impact of puddling, tillage and residue management on wheat (Triticum aestivum, L.) seedling emergence and growth in a rice–wheat system using nonlinear regression models. – Soil and Tillage Research 87(1): 119-130.
[47] Ning, P., Li, S., Yu, P., Zhang, Y., Li, C. (2013): Post-silking accumulation and partitioning of dry matter, nitrogen, phosphorus and potassium in maize varieties differing in leaf longevity. – Field Crops Research 144: 19-27.
[48] Rebetzke, G. J., Ellis, M. H., Bonnett, D. G., Condon, A. G., Falk, D., Richards, R. A. (2011): The Rht13 dwarfing gene reduces peduncle length and plant height to increase grain number and yield of wheat. – Field Crops Research 124(3): 323-331.
[49] Richard, F. J. (1959): A flexible growth function for empirical use. – Journal of experimental Botany 10(2): 290-301.
[50] Sepaskhah, A. R., Fahandezh-Saadi, S., Zand-Parsa, S. (2011): Logistic model application for prediction of maize yield under water and nitrogen management. – Agricultural Water Management 99(1): 51-57.
[51] Shabani, A., Sepaskhah, A. R., Kamgar-Haghighi, A. A., Honar, T. (2018): Using double logistic equation to describe the growth of winter rapeseed. – The Journal of Agricultural Science 156(1): 37-45.
[52] Shi, X. F., Chou, S. Y., Shi, Z. L., Xie, F. L., Gao, W., Song, L. H. (2017): Effect of sowing date and sowing amount on population traits and yield of winter wheat cultivar Yaomai 16. – Journal of Triticeae Crops 37(2): 1-9 (in Chinese with English abstract).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_25392556

[53] Sun, Y., Wu, C. S., Gu, Y. (2017): Effects of nitrogen fertilizer on chlorophyll fluorescence characteristics and yield of maize under mulched drip irrigation in semi-arid area. – Journal of Maize Sciences 25(1): 133-138, 146 (in Chinese with English abstract).
[54] Tao, H., Feng, H., Xu, L., Miao, M., Yang, G., Yang, X., Fan, L. (2020): Estimation of the yield and plant height of winter wheat using UAV-based hyperspectral images. – Sensors 20(4): 1231.
[55] Teng, K. (2012): Effects of sowing quantity and additional quantity of nitrogen fertilizer on growth and development, yield and quality of wheat (Triticum aestivum Linn.). – Journal of Anhui Agricultural Sciences 40(24): 11980-11983 + 12062 (in Chinese with English abstract).
[56] Tian, S., Li, H., Bai, W. (2012): Effect of narrow spaced sparse drilling planting technique on population and yield of winter wheat in late-maturing winter wheat region of Central Shanxi. – Journal of Triticeae Crops 32(6): 1107-1110 (in Chinese with English abstract).
[57] Van Diepen, C. V., Wolf, J., Van Keulen, H., Rappoldt, C. (1989): WOFOST: a simulation model of crop production. – Soil Use and Management 5(1): 16-24.
[58] Verhulst, P.-F. (1838): Notice sur la loi que la population suit dans son accroissement. – Correspondance Mathématique et Physique Publiée par A 10: 113-126.
[59] Wang, Y. Q., Tao, H. B., Huang, S. B., Xu, L. N., Yang, L. H., Qi, L. P., Wang, P. (2013): Effects of nitrogen patterns on nitrogen use and yield benefit of summer maize. – Journal of Nuclear Agricultural Sciences 27(2): 219-224 (in Chinese with English abstract).
[60] Wang, X. X., Wang, Q. J., Fan, J., Sun, L. J. (2014): Logistic model analysis of winter wheat growth on China’s Loess Plateau. – Canadian Journal of Plant Science 94(8): 1471-1479.
[61] Wang, K., Su, L., Wang, Q. (2021): Cotton growth model under drip irrigation with film mulching: a case study of Xinjiang, China. – Agronomy Journal 113(3): 2417-2436.
[62] Wardhani, W. S., Kusumastuti, P. (2014): Describing the height growth of corn using Logistic and Gompertz model. – AGRIVITA, Journal of Agricultural Science 35(3): 237-241.
[63] Wu, Z., Wang, Q. (2009): Effects of deficit irrigation with brackish water on soil water-salt distribution and winter wheat yield. – Transactions of The Chinese Society of Agricultural Engineering 25(9): 36-42 (in Chinese with English abstract).
[64] Xiao, J. F., Nan, J. Q., Liu, Z. D., Yu, J. H. (2010): Study on yield and yield components of summer maize under different groundwater levels. – Agricultural Research in the Arid Areas 28(6): 42-45 (in Chinese with English abstract).
[65] Xiao, J. F., Liu, Z. D., Liu, Z. G., Nan, J. Q. (2011): Effects of drought at different growth stages and different water availabilities on growth and water consumption characteristics of summer Maize. – Journal of Maize Sciences 4: 54-58 (in Chinese with English abstract).
[66] Yang, L., Jia, Z., Han, Q., Yang, W., Yang, B., Ding, R., Yang, H. (2015): Effects of water-fertilizer coupling on biomass and photosynthetic characteristics of flag leaf of winter wheat. – Journal of Northwest A&F University (Nat Sci Ed) 43(12):1-9 (in Chinese with English abstract).
[67] Yin, X., McClure, M. A., Jaja, N., Tyler, D. D., Hayes, R. M. (2011): In-season prediction of corn yield using plant height under major production systems. – Agronomy Journal 103(3): 923-929.
[68] Yin, S., Li, P., Xu, Y., Liu, J., Yang, T., Wei, J., Hao, D. (2020): Genetic and genomic analysis of the seed-filling process in maize based on a logistic model. – Heredity 124(1): 122-134.
[69] Zhang, M., Deng, Z., Zhao, M., Huang, B. (2004): Analysis of dry matter accumulation of winter wheat on Loess Plateau of Long Dong. – Chinese Journal of Agrometeorology 25(4): 14-17 (in Chinese with English abstract).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_25392556

[70] Zhang, J. P., Sun, J. S., Liu, Z. G., Gao, Y., Liu, X. F., Li, X. D. (2008): Effects of different mulching and soil moisture treatments on growth development and water consumption characteristics of summer maize. – Water Saving Irrigation 9: 13-17 (in Chinese with English abstract).
[71] Zhang, X. Q., Du, S. Z., Cao, C. F., Qiao, Y. Q., Zhao, Z., Zhang, Y. L. (2014): Effects of sowing date on populations, yield and chlorophyll fluorescence characteristics of winter wheat. – Journal of Triticeae Crops 34: 71-77 (in Chinese with English abstract).
[72] Zhang, Z., Zhong, W. W., Wang, X. Y., Chen, Y. H., Zhou, X. B. (2017): Effect of cultivation measures of previous winter wheat on following summer maize photosynthesis characteristics and yield. – Acta Agriculturae Boreali-Sinica 32(4): 155-161 (in Chinese with English abstract).
[73] Zhang, P., Gu, S., Wang, Y., Xu, C., Zhao, Y., Liu, X., Huang, S. (2023): The relationships between maize (Zea mays L.) lodging resistance and yield formation depend on dry matter allocation to ear and stem. – The Crop Journal 11(1): 258-268.
[74] Zhu, B. G., Zhang, C. F., Wang, N. N., Meng, Q. Y., Jia, H. B., Kuang, E. J. (2015): Effects of different nitrogen topdressing methods on correlated character and yield of maize in cold zone. – Journal of Nuclear Agricultural Sciences 29(9): 1806-1812 (in Chinese with English abstract).

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DOI: http://dx.doi.org/10.15666/aeer/2103_25392556