Logistic model analysis of winter wheat growth on China's Loess Plateau

Wang Xiangxiang[1,2], Wang Quanjiu[1,3,6], Fan Jun[1,2], Su Lijun[4], and Shen Xinlei[5]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling 712100, Shaanxi, P. R. China; [2]Graduate University of Chinese Academy of Science, 100039, Beijing, P. R. China; [3]Institute of Water Resource Research, Xian University of Technology, 710048, Xian, P. R. China; [4]School of Sciences, Xian University of Technology, 710054, Xian, P. R. China; and [5]Luohe Soil and Fertilizer Extension Service, 462300, Luohe, P. R. China.
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Xiangxiang, W., Quanjiu, W., Jun, F., Lijun, S. and Xinlei, S. 2014. **Logistic model analysis of winter wheat growth on China's Loess Plateau**. Can. J. Plant Sci. **94**: 1471–1479. The leaf area index (LAI) and above-ground biomass are closely related to crop growth status and yields. Therefore, analysis of their variation and development of a mathematical model for their prediction can provide a theoretical basis for further research. This paper presents a new equation for logistic pattern that calculates above-ground biomass and LAI for different irrigation treatments independent of growing degree days (GDD) and plant height. The model root mean square of error (RMSE) for the LAI was from 0.25 to 1.36, and for above-ground biomass it was from 0.49 to 1.34. The r^2 values for the model's output under the single irrigation, double irrigation, triple irrigation, and quadruple irrigation treatments were 0.98, 0.87, 0.96, 0.98 and 0.99, respectively. For above-ground biomass they were 0.96, 0.97, 0.99, 0.97, and 0.97, respectively. The relative error for LAI ranged from 0.026 to 15.2%. For above-ground biomass, the Re ranged from 5.78 to 8.79%. The results gave good agreement between the estimated values and the measured values. The Logistic model was good at estimating the LAI and the above-ground biomass from the plant height.

Key words: Logistic model, growing degree day, leaf area index, plant height, model validation

Xiangxiang, W., Quanjiu, W., Jun, F., Lijun, S. et Xinlei, S. 2014. **Analyse de la croissance du blé d'hiver sur le plateau de læss chinois au moyen d'un modèle logistique**. Can. J. Plant Sci. **94**: 1471–1479. L'indice de la superficie foliaire (ISF) et la biomasse aérienne présentent d'étroites relations avec la croissance et le rendement des cultures. Analyser leur variation et créer un modèle mathématique permettant de les prévoir pourraient donc servir de fondement théorique à des recherches plus poussées. L'article propose une nouvelle équation pour un schéma logistique permettant de calculer la biomasse aérienne et l'ISF sous divers régimes d'irrigation, selon le nombre de degrés-jours de croissance et la hauteur des plants. Le modèle a un écart-type de 0,25 à 1,36 pour l'ISF et de 0,49 à 1,34 pour la biomasse aérienne. La valeur de r^2 s'établit respectivement à 0,98, 0,87, 0,96, 0,98 et 0,99 pour la culture sous irrigation simple, double, triple ou quadruple, comparativement à 0,96, 0,97, 0,99, 0,97 et 0,97 pour la biomasse aérienne. La valeur Re de l'ISF fluctue de 0,026 % à 15,2 %, contre 5,78 % à 8,79 % pour la biomasse aérienne. Ces résultats révèlent une bonne concordance entre les valeurs estimées et les valeurs réelles. Le modèle logistique autorise une bonne estimation de l'indice de la superficie foliaire et de la biomasse aérienne en fonction de la hauteur des plantes.

Mots clés: Modèle logistique, degrés-jours de croissance, indice de la superficie foliaire, hauteur du plant, validation de modèle

Dryland farming is common in northern China, and agricultural dryland accounts for around 55% of China's total cultivated land (Xin and Wang 1998). The low and variable rainfall in the dry plain region of China restricts the scope for rain-fed crop production. The soil water availability is the main factor limiting crop production on the Loess Plateau. Some reports indicate that improving crop water productivity could stabilize yields (Ghahraman and Sepaskhah 1997; Pereira et al. 2002) and deficit irrigation has been proposed as an irrigation strategy that may be useful for this purpose (Ghahraman and Sepaskhah 1997; Lecoeur and Guilioni 1998; Kipkorir et al. 2002; Debaeke and Aboudrare 2004; Fereres and Soriano 2007; Farré and Faci 2009).

For wheat production, plant height, leaf area index (LAI), and dry matter accumulation are important indicators of growth status, and their values are closely related to dry matter production. Under soil water deficit conditions, plant leaf expansion is reduced as a result of both a reduction in the rate of leaf production and in the rate of individual leaf expansion (Lecoeur and Guilioni 1998). Therefore, analyzing the variation characteristics of wheat growth indices and proposing mathematical models under deficit irrigation can

[6]*Corresponding author (e-mail: wquanjiu@163.com).*

Abbreviations: **GDD**, growing degree days; **LAI**, leaf area index provide a theoretical basis for water consumption and yield prediction. The measurement of leaf area is laborious and time-consuming. The Logistic model and its extended variants are usually used to simulate crop growth. No previous research has studied LAI and dry matter accumulation process using the Logistic model or the expanded form (Darroch and Baker 1990; Thornley and Johnson 1990; Duguid and Brûlé-Babel 1994). Wiegand et al. (1979) estimated LAI from earth observation satellite data implemented for large areas. Lecoeur and Guilioni (1998) developed a qualitative function between the rate of leaf production and soil water deficit. Yu et al. (1995) simulated the accumulation of rice biomass and LAI using a universal growth model. However, Logistic models are subjected to certain restrictions because of the field experiment error and the difficulty of controlling the accuracy of the model parameters. Accumulated temperature may be more representative than time as a basis for crop growth and development (Lecoeur and Guilioni 1998), and accumulated temperature can reduce the effects of differing temperature regimes and growth years among experiments (Russelle et al. 1984). Detailed Logistic model evaluation of winter wheat under different water supply conditions is still lacking in the region. Therefore, in this paper, a modified equation for Logistic pattern of determinate wheat growth is established. Based on variation characteristics of wheat plant height, biomass and LAI, a new Logistic equation was presented with growing degree days (GDD) and water consumption. Simple measurements of wheat height can be used as a rapid and low-cost estimate for LAI and above-ground biomass in the logistic model to simulate wheat growth conditions on the Loess Plateau.

MATERIALS AND METHODS

Site Description

The data used in this work were collected between 2006 and 2011 at the Changwu Agri-ecological Station on the Loess Plateau (lat. 35D28′N, long. 107D88′E) in the Shaanxi Province of China. The experimental site is located about 1206 m above sea level. The loess at the site is more than 100 m deep, and the soil is a Cumuli-Ustic Isohumosol according to the Chinese Soil Taxonomy system (Gong et al. 2007), containing 37% clay, 59% silt, and 4% sand. The average soil pH is 8.4, and its bulk density is 1.35 g cm^{-3}. The saturated hydraulic conductivity is 240 mm d^{-1}. The soil's contents of organic matter, total nitrogen, available phosphorus, available potassium and inorganic nitrogen are 11.8 g kg^{-1}, 0.87 g kg^{-1}, 14.4 mg kg^{-1}, 144.6 mg kg^{-1} and 3.15 mg kg^{-1}, respectively. The field capacity, saturated water content, permanent wilting point and threshold point are 0.29, 0.46, 0.1 and 0.21, respectively. The depth of groundwater in the study area is up to 50–80 m. Winter wheat root cannot obtain water from the groundwater.

Ethics Statement

The experimental site is managed by the Institute of Soil and Water Conservation of the Graduate University of the Chinese Academy of Science and is available for teaching and research by the university. This study did not involve any endangered or protected species.

Field Experimental Design

Each experimental plot had an area of 16 m^2, and five different irrigation treatments were tested. The treatments were applied using a randomized complete block design with four replicates for each treatment. Fertilizer was applied to the plots in the middle of September during each year of the experiment and the "changhan-58" wheat variety was sown immediately afterwards. The wheat was harvested at the end of the following June, and plots were left fallow between July and September. The plots were separated from each other using 1-m buffers and plastic sheets of about 0.4 m deep. Five growth stages were defined: over-wintering, turning green, stem elongation, flowering, and grain filling. According to the climate of the region, 75 mm water was applied each time to secure the irrigation diversity in different typical hydrologic years. Irrigation water was applied using the surface flood method. In the deficit irrigation treatments, irrigation was withheld during some or all of the over-wintering, turning green, stem elongation, flowering and grain filling stages. In the single irrigation treatment, irrigation was applied during the over-wintering stage only. For the double irrigation treatment, irrigation was applied during the over-wintering and turning green stages, and so forth (Table 1).

Plant height (H) was measured from the beginning of the water treatment at each growth stage. Leaf area index was measured using a LAI-2000 Plant Canopy Analyser. Dry matter accumulation of winter wheat was measured at the beginning of the water treatments. The above-ground parts were put into an oven for 30 min at 105°C and then dried at 75°C until a constant weight was achieved.

Statistical Analysis

The Logistic model is obtained by a simple algebraic transformation, and the parameters are fitted out with

Table 1. Irrigation treatments and schedule for the experimental design in the winter wheat growing seasons

	Irrigation treatment (mm)					
Irrigation schedule	W_1	W_2	W_3	W_4	W_5	W_0
Over-wintering	75	75	75	75	75	0
Turning green	0	75	75	75	75	0
Stem elongation	0	0	75	75	75	0
Flowering	0	0	0	75	75	0
Grain filling	0	0	0	0	75	0
Irrigation amount (mm)	75	150	225	300	375	0

the least square method. The bias in the total difference between simulation and measurement was determined by calculating the correlation coefficient (R^2) and the root mean square error (RMSE).

The root mean square error (RMSE) reflects a measure (%) of the relative difference between estimated and observed data. The root mean square error is defined by the function

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

The estimations are considered to be excellent when the normalized RMSE is less than 10%, good if the normalized RMSE is between 10 and 20%, fair if normalized RMSE is between 20 and 30%, and poor if the normalized RMSE is greater than 30%.

The correlation coefficient (R^2) is another method for evaluating the magnitude of the difference between the measured values and the predictions generated using a model. The greater the R^2 value, the lower the deviation between the model results and the observation.

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - MO)^2}\right]$$

In this work, the relative error is defined using the function:

$$RE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n} P_i^2}\right]$$

Where P_i and O_i are estimated and observed values, respectively, and n is the number of observations. MO is the mean observed variable.

Description of the Model

The Logistic model was first put forward by the Dutch biologist and mathematician Verhulst. A Logistic model has been used to describe population growth (Coleman 1981) and crop growth. It was known as a growth curve (Loss et al. 1989). The form of the Logistic model is:

$$y = k/(1 + e^{a+bt}) \quad (1)$$

where y is population density, t is time, a and b and k are parameters.

In order to improve the model for describing LAI with time, Wang (1986) put forward a correction model. The form of logistic model and its correction model is:

$$x = x_m/(1 + e^{a+bt+ct^2}) \quad (2)$$

where x is LAI, t is time, and a, b, c, and x_m are parameters.

Numerous studies have demonstrated the usefulness of GDD for predicting crop growth and development, classifying crop species, hybrids and varieties, or evaluating climates for specific crop-management combinations (Blackman 1919; Cross and Zuber 1972; Tscheschke and Gilley 1979). Most of the research proposed that GDD show significantly greater correlation with plant growth and development than does accumulated time (Tollenaar et al. 1979; Coelho and Dale 1980; Kiniry and Keener 1982).

Crop growth is closely related to the accumulated temperature value. The required accumulated temperature of a crop is basically stable during the whole growth period, although the location and growth periods are different. Therefore, the accumulated temperature can reduce the differences related to the crop growth year and location (Russelle et al. 1984). Thus, we modified the logistic model based on effective accumulated temperature, as follows:

$$x = (x_m + \alpha)/(1 + e^{a+bGDD}) \quad (3)$$

$$x = (x_m + \alpha)/(1 + e^{a+bGDD+cGDD^2}) \quad (4)$$

where x is LAI or biomass or plant height, x_m is the maximum value, GDD is the growing degree days, a and b and c are undetermined coefficients. α is a correction coefficient which is fitted out. In the traditional form of the logistic model, x is always less than the x_m. If the x_m is the maximum of measurement, x is sometimes more than x_m, so the correction coefficient is given.

The GDD are calculated by subtracting the base temperature from the average air temperature as follows (McMaster and Wilhelm 1997):

$$GDD = \sum_{i=1}^{n}(Tavg_i - Tbase_i) \quad (5)$$

where $Tavg$ is the average temperature, and $Tbase$ is the base temperature.

$$T_{avg} = \frac{(T_x^* + T_n^*)}{2} \quad (6)$$

T_x^* is the appropriate highest temperature, and T_n^* is the appropriate lowest temperature. The formulas used to define them are:

$$\begin{cases} T_x^* = T_{upper} & if: T_x^* \geq T_{upper} \\ T_x^* = T_{base} & if: T_x^* \leq T_{base} \\ T_x^* = T_x & other \end{cases} \quad (7)$$

and

$$\begin{cases} T_n^* = T_{upper} & if: T_n^* \geq T_{upper} \\ T_n^* = T_{base} & if: T_n^* \leq T_{base} \\ T_n^* = T_n & other \end{cases} \quad (8)$$

For winter wheat, the base temperature is 0°C and t_{upper} is 30°C. The calculated GDD and the measured average temperatures are presented in Fig. 1.

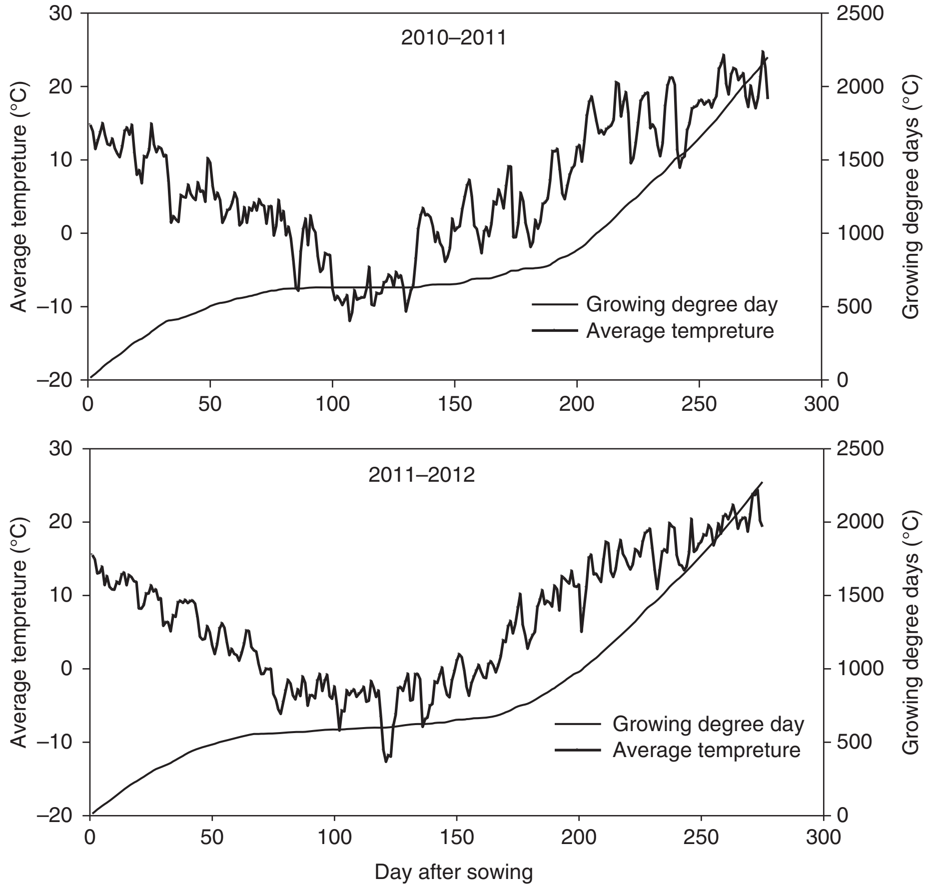

Fig. 1. Temperature and growing degree days for the winter wheat during 2007–2008, 2010–2011 and 2011–2012 growing seasons.

RESULTS AND DISCUSSION

Plant Height and Logistic Model Parameters

As shown in Fig. 2, from 2011 Mar. 30 (GDD > 800), with increasing temperatures, the growth of the winter wheat accelerated. At this time, winter wheat began to turn green and the plant height increased significantly. From 2011 May 25 (1600 < GDD < 1800), the treatments reached maximum plant height. Quadruple irrigation produced the greatest plant height (87.1 cm), followed by double irrigation (80.2cm); no irrigation had the minimum value in plant height (69.3 cm). Different irrigation treatments gave different rates of increase in plant height. They were 0.98, 1.07, 1.16, 1.10, and 1.26 cm d^{-1}, respectively. Since head sprouting, all treatments had constant plant height values.

The Logistic curve was used to analyze the process of plant height change under different irrigation treatments. The plant height of winter wheat was calculated based on Eq. 3

$$H = (H_m + \alpha)/(1 + e^{a_1 + b_1 GDD})$$

where H is the plant height (cm) and H_m is the maximum plant height (cm). The results of fitting the equation to the experiment data are presented in Table 2. The maximum plant height (H_m)

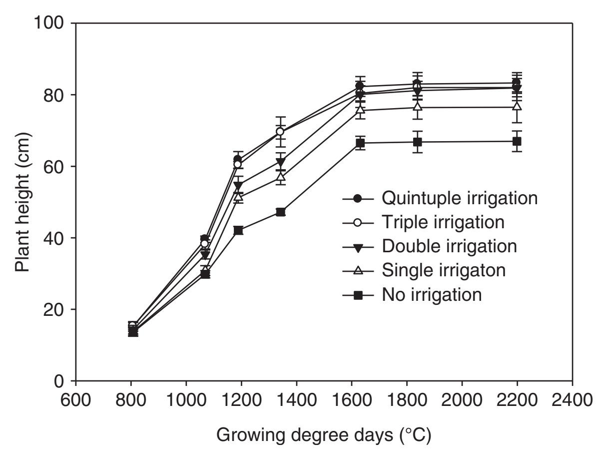

Fig. 2. Plant height versus growing degree days for different irrigation treatments.

Table 2. Parameter values of the Logistic model to wheat plant height in ChangWu, China (2011)

Irrigation treatments	a_1	b_1	H_m	R^2
W_0	6.7542	−0.00632	67.05	0.9626
W_1	7.0615	−0.00657	76.56	0.9869
W_2	6.6514	−0.00611	81.91	0.9504
W_3	6.8235	−0.00657	82.06	0.9757
W_4	6.4953	−0.00624	83.34	0.9917
Average	6.7572	−0.00636		
S^2	0.1219	1.55E-07		$\alpha = 0.1$

increased with increasing the irrigation quota. However, the parameters a_1 and b_1 were nearly constant (Table 2).

Leaf Area Index and Logistic Model Parameters

The LAI curve differed from the classical form of the logistic curve model for wheat growth. The LAI reached maximum values at the flowering or grain-filling stages. The maximum values were slightly earlier than the plant height. From 2011 May 10 ($1200 < GDD < 1400$), different treatments had the maximum value S in LAI. Quadruple irrigation gave the highest LAI (8.87), followed by double irrigation (7.56), while no irrigation gave the minimum LAI value (5.12). The LAI decreased in the later stages, and dropped at the late reproductive growth stage (Fig. 3). Different irrigation treatments have different rates of increase of LAI. They were 0.11, 0.11, 0.16, 0.19, and 0.15 d^{-1}, respectively. Therefore, the classic form of the logistic curve model was amended to describe LAI. Accordingly, we can have the LAI amended

logistic model (Eq. 4), $L = \frac{L_m + \alpha}{1 + e^{(a_2 + b_2 GDD + cGDD^2)}}$.

where L is the LAI and L_m is the maximum LAI.

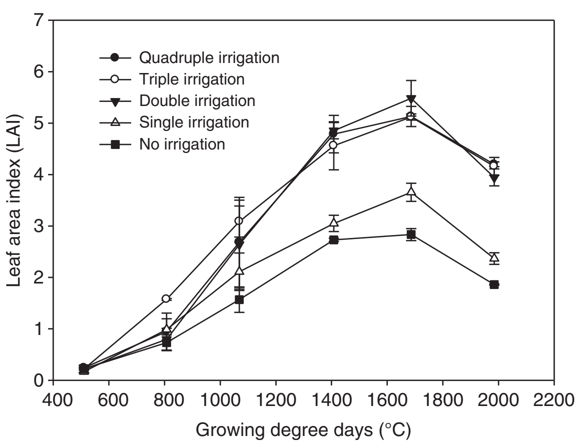

Fig. 3. The leaf area index (LAI) versus growing degree days for different irrigation treatments.

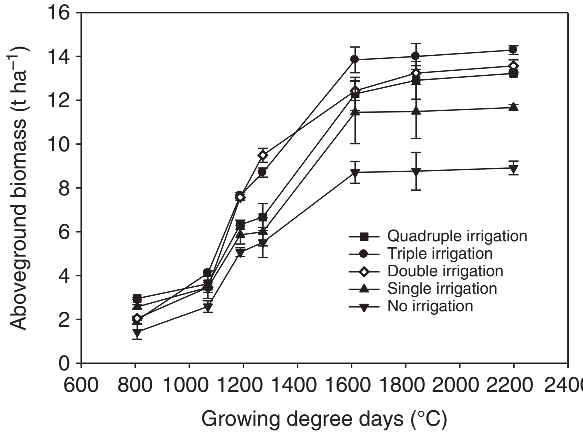

Fig. 4. The above-ground biomass versus growing degree days for different irrigation treatments.

Above-ground Biomass and Logistic Model Parameters

As shown in Fig. 4, growth of the above-ground biomass was similar to the plant height. With increasing air temperature, when winter wheat began to turn green, the above-ground biomass increased significantly. From 2011 Jun. 01 ($1600 < GDD < 1800$), growth slowed. After reaching full maturity, the different treatments reached maximum biomass values. For different irrigation treatments, the values were 8.908, 11.667, 13.569, 14.289, and 13.224 t ha^{-1}, respectively. The above-ground biomass of winter wheat was described with Eq. 3, $B = (B_m + \alpha)/(1 + e^{a_3 + b_3 GDD})$. Where B is above-ground biomass (t ha^{-1}) and B_m is the maximum above-ground biomass (t ha^{-1}).

The Winter Wheat Growth Model

Normalization of the Parameters

As shown in the results (Tables 2–4), analysis of variance indicated that the parameters (a1, b1, a2, b2, a3, b3, c) change little between the different treatments. This suggests that the different irrigation quota have little impact on the shape of the model. So we can average the different parameters for different irrigations and get a set of standardized parameters. Standardized

Table 3. Parameter values of the Logistic model to wheat leaf area index (LAI) in ChangWu, China (2011)

Irrigation treatments	a_2	b_2	c	L_m	R^2
W_0	7.8488	−0.0086652	2.8021e-006	2.81	0.9767
W_1	8.3746	−0.0096971	3.1499e-006	3.63	0.9430
W_2	8.5582	−0.0098386	3.0273e-006	5.25	0.9781
W_3	8.2226	−0.0098411	3.1238e-006	5.42	0.9693
W_4	8.1099	−0.0092517	2.8265e-006	5.21	0.9989
Average	8.2228	−0.0094587	2.9859E-06		
S^2	0.2780	9.86E-07			$\alpha = 9$

Table 4. Parameter values of the Logistic model to wheat above-ground biomass accumulation in Changwu, China (2011)

Irrigation treatments	a_3	b_3	B_m	R^2
W_0	6.0607	−0.00526	8.93	0.9827
W_1	6.2525	−0.00548	11.68	0.9338
W_2	6.2884	−0.00538	13.57	0.9745
W_3	6.5722	−0.00566	14.30	0.9877
W_4	6.2356	−0.00531	13.22	0.9528
Average	6.2819	−0.00542		
S^2	0.1345	9.08E-08		$\alpha = 0.05$

parameters are the relative average values of the five irrigation treatments.

The parameters for different irrigations are normalized, and for the different irrigation treatments, the equations are given by:

$$\frac{H_m + \alpha}{H} = 1 + e^{6.75718 - 0.00636GDD} \quad (9)$$

$$\frac{L_m + \alpha}{L} = 1 + e^{(8.2228 - 0.0094587GDD + 2.9859*10^{-6}GDD^2)} \quad (10)$$

$$\frac{B_m + \alpha}{B} = 1 + e^{6.28188 - 0.0054171GDD} \quad (11)$$

After normalizing the parameters, we use models 9–11 to estimate plant height, LAI and above-ground biomass. The relative errors of measured and estimated values are listed in Table 5. The results show that the deviation is less than 10% except for LAI for no irrigation and triple irrigation. We can conclude that the irrigation amount has little effect on the parameters. The normalized parameters are advisable.

Relationships Between Water Consumption and Maximum Plant Values

The irrigation amounts have little effect on the parameters. However, the maximum values of plant height, LAI and above-ground biomass for the different irrigation treatments differ and are related to the amount of water consumed. Figure 5 shows that the r^2 of the plant height, LAI and above-ground biomass were 0.93, 0.80, and 0.94, respectively. The irrigation amounts have a small effect on the shape of the curves. However, water consumption affects the maximum values according to the following equations, which are fitted out and shown in Fig. 5:

$$f_1(x) = -0.0002x^2 + 0.2504x + 11.4765 \quad (12)$$

$$f_2(x) = 2.035*10^{-5}x^2 + 0.0278x - 4.1899 \quad (13)$$

$$f_3(x) = -3.8907*10^{-5}x^2 + 0.05x - 2.5292 \quad (14)$$

Table 5. The Re of the plant height, leaf area index and above-ground biomass

Re	Plant height	Leaf area index	Above-ground biomass
Irrigation treatment			
W_0	11.56	2.09	1.09
W_1	11.32	1.77	0.36
W_2	8.30	1.43	0.50
W_3	7.33	1.27	0.75
W_4	0.04	0.16	0.06

Relation of Plant Height and Leaf Area Index

As in Eq. 9, $\frac{H_m}{H} = 1 + e^{6.75718 - 0.00636GDD}$

$$\text{consequently, } GDD = \frac{\ln\left(\frac{Hm}{H} - 1\right) - 6.75718}{-0.00636} \quad (15)$$

and, as in Eq. 10, $\frac{L_m}{L} = 1 + \exp(8.2228 - 0.0094587GDD + 2.9859*10^{-6}GDD^2)$

Substituting Eq. 14 and Eq. 15 into Eq. 10, we get Eq. 16

$$L = \left[f_2(x) + 9]\middle/\left(1 + \exp\left\{8.228 - 0.0094587 \cdot \frac{\ln\left(\frac{f_1(x)}{H} - 1\right) - 6.75718}{-0.00636} + 2.9859*10^{-6} \cdot \left(\frac{\ln\left(\frac{f_1(x)}{H} - 1\right) - 6.75718}{-0.00636}\right)^2\right\}\right)\right. \quad (16)$$

Equation 16 is a relationship between LAI and plant height, obtained by multiple regressions. The average values of the parameters are presented in Tables 2 and 3. Equation 16 was used to estimate LAI by measured values of plants' height and water consumption. In Fig. 6, the estimated LAI values were similar to the measured values. The LAI was well estimated by wheat plant height, as shown when compared with the observed values. Therefore, if the field situations are limited, the LAI can be estimated by measuring plant height.

Relation of Plant Height and Above-ground Biomass

Equation 11 is:

$$B = (B_m + \alpha)/[1 + \exp(6.28188 - 0.0054171\text{GDD})]$$

and substituting Eq. 13 and Eq. 15 into Eq. 11. Consequently,

$$B = \left[f_3(x) + \alpha]\middle/\left\{1 + \exp\left[6.28188 - 0.0054171 \cdot \left(\frac{\ln\left(\frac{f_1(x)}{H} - 1\right) - 6.75718}{-0.00636}\right)\right]\right\}\right. \quad (17)$$

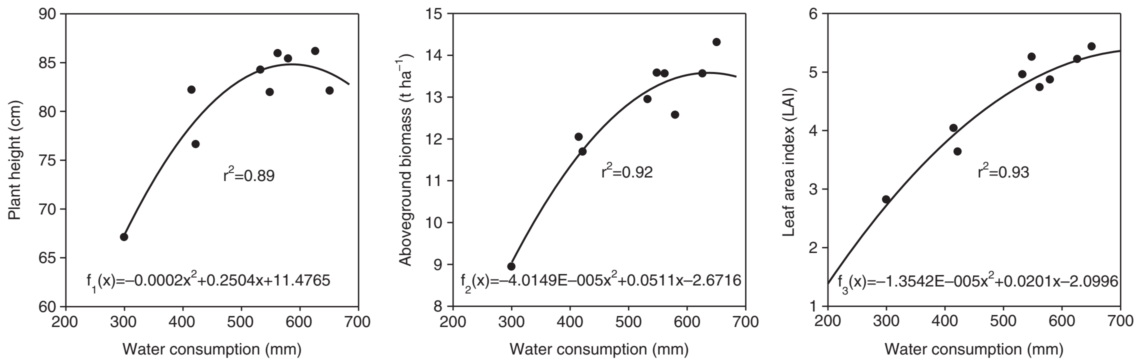

Fig. 5. The relationship between plant height, leaf area index and biomass and water consumption.

The parameters used for calibrating the Logistic model are presented in Table 2 and Table 4. Equation 17 was used to estimate above-ground biomass using measured values of plant height.

Equation 16 shows the relationship between LAI and height. Equation 17 shows the relationship between above-ground biomass and height. Leaf area index and above-ground biomass can then be calculated from plant height.

Model Validation

The logistic model estimating the LAI under the different irrigations were performed for the 2011–2012 growing season; the results obtained were generally in good agreement with observations (Fig. 6).

In Fig. 7, the above-ground biomass also had good agreement between the estimated values and measured values. The above-ground biomass was estimated well by wheat plant height when compared with the observed values.

Figures 6 and 7 showed the deviations of the estimated LAI and above-ground biomass. Lower RMSE values indicated a good performance of the model. The model root mean square of error (RMSE) showed moderate performance for LAI (RMSE = 0.09–0.54) and above-ground biomass (RMSE = 0.54–0.69), and the RMSE values of the LAI were smaller than those of the above-ground biomass. The smallest RMSE value of LAI was 0.09 and the smallest value of above-ground biomass was 0.54. For LAI, the r^2 values for the model's output under the single irrigation, double irrigation, triple irrigation, and quadruple irrigation treatments were 0.98, 0.87, 0.96, 0.98 and 0.99, respectively. For above-ground biomass, they were 0.96, 0.97, 0.99, 0.97, and 0.97, respectively. The Re for LAI ranged from 0.026 to 15.2%. For above-ground biomass, the Re ranged

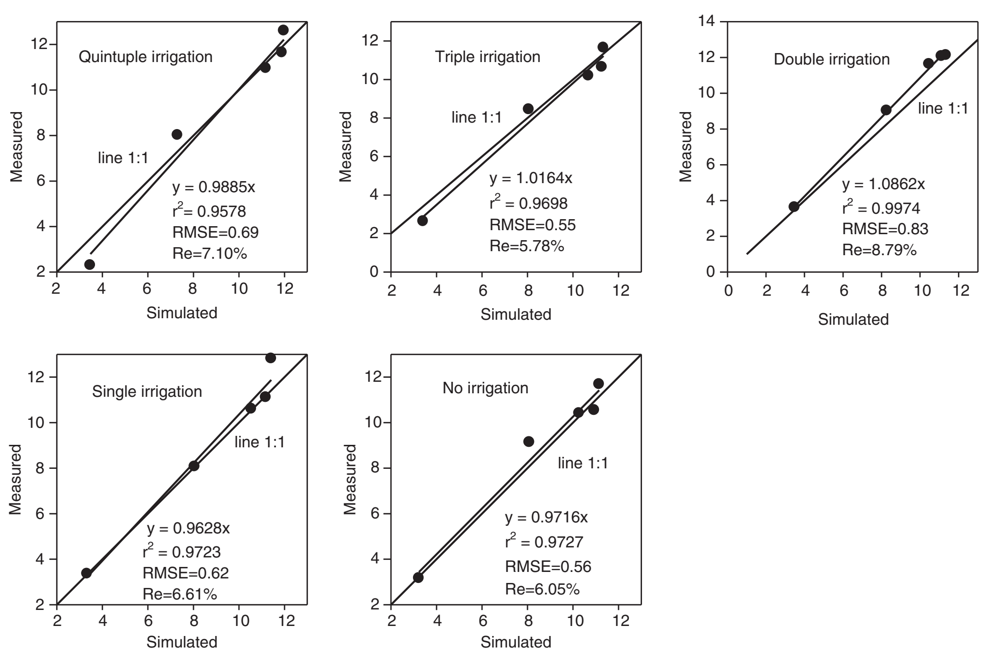

Fig. 6. Comparison of simulated and measured leaf are index for the 2011–2012 growing season.

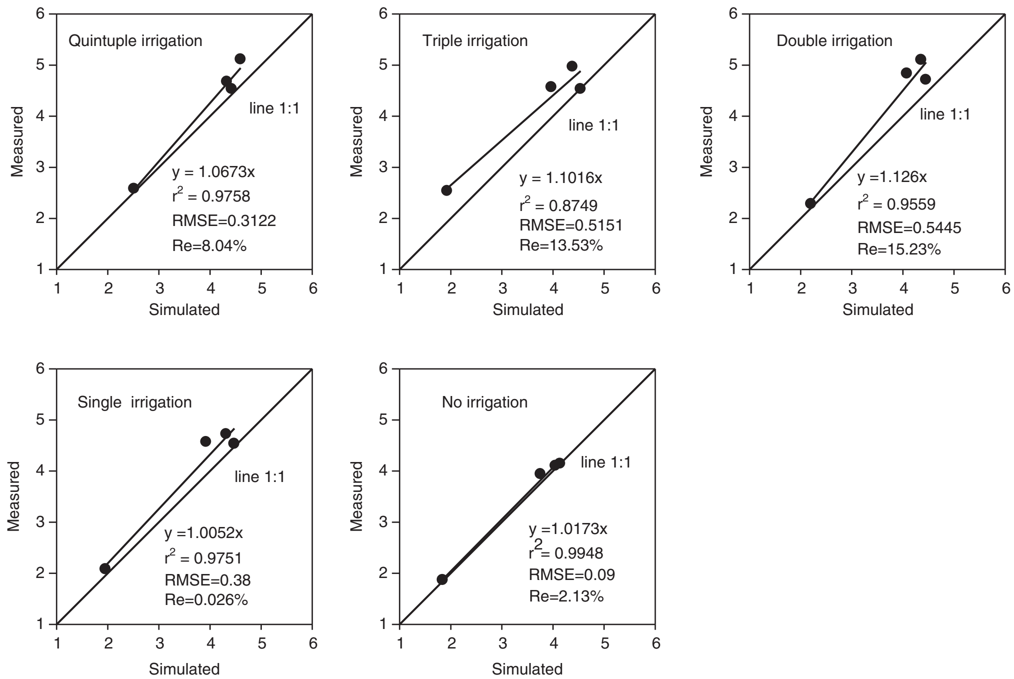

Fig. 7. Comparison of simulated and measured above-ground biomass for the 2011–2012 growing season.

from 5.78 to 8.79%. This suggests that the Logistic model was useful for estimating the LAI and above-ground biomass from the plant height.

CONCLUSION AND DISCUSSION

In wheat production, plant height, LAI and above-ground biomass are important parameters. All of them are quantitative indices of plant structure, which can reflect wheat growth conditions, and indirectly affect the yield.

Compared with other treatments, the lowest irrigation level (W0) of winter wheat performed with lower growth rate and was earlier maturing. During the period of growth, the winter wheat grew ahead of schedule, in that the soil was excessively dry. At the same time, the highest irrigation level gave greater plant height, delayed, but not the highest grain yield. The best irrigation treatment on China's Loess Plateau was W2 (150 mm).

Irrigation amount had little effect on the model parameters. Water consumption only affected the maximum value. Therefore, new Logistic curve equations were based on plant height of the winter wheat. The plant heights were used to calculate the LAI and the above-ground biomass by the new Logistic curve equations for different irrigation treatments. The results gave good agreement between the estimated values and the measured values. The Logistic model was good at estimating the LAI and above-ground biomass from plant height.

There is an affinity relationship between LAI and temperature. In the high-temperature region, the growth of the leaf was rapid; however, in the low temperature region, the growth rate was slow (Yu et al. 1995). Crop growth is closely related to the accumulated temperature. The required accumulated temperature of a crop is basically stable during the whole growth period, although the location and growth periods are different. Using GDD to simulate the wheat growth model has widespread applicability. The classic Logistic growth model only uses time as the parameter; however, in this experiment we used plant height and GDD as variables to simulate growth. Different regions and treatments provide different plant heights, so using plant height to simulate plant growth conditions in the logistic model can provide more accurate information on plant growth conditions, although, the logistic model with accumulated temperature can reduce differences related to location and variety (Wang et al. 1995). Additional research on the effect of location and variety is needed to increase the applicability of the model.

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