CONSTRUCTION AND EVALUATION OF SIMULATION MODEL FOR THE GROWTH AND DEVELOPMENT OF MILLET IN ARID AREAS
/
干旱区谷子生长发育模拟模型的构建与评价

Yuzhi WANG [1], Yaoyu LI [1], Tengteng QU [1], Siyu WANG [1], Lili SUN [2], Wuping ZHANG [1*], Fuzhong LI [1*]
[1] College of Software, Shanxi Agricultural University, Taigu, Shanxi / China
[2] College of Agricultural Engineering, Shanxi Agricultural University, Taigu, Shanxi / China
Corresponding authors: Tel: +8603546287093; Zhang Wuping; E-mail: zwping@126.com;
Li Fuzhong E-mail: sxaulfz@126.com
DOI: https://doi.org/10.35633/inmateh-71-55

Keywords: *Millet, Photosynthesis, Biomass allocation, Functional-structural plant model*

ABSTRACT
The establishment of crop growth models enables the simulation of the impacts of environmental changes on crop growth, providing theoretical guidance for exploring the relationship between environmental factors and crop growth. The model used the growth cycle (GC) as the simulation time step and was built upon four sub-models: topology, photosynthesis, biomass allocation, and geometric morphology. It was quantitatively utilized the concept of effective accumulated temperature (EAT) and parameters such as sink and expansion rate were used to explain the allometric growth relationships among different organs. The R2 values for the geometric morphological parameters such as leaf length, leaf width, leaf area, and internode volume ranged from 0.78 to 0.94, while the F-values for the regression equations ranged from 1533.53 to 13949.51. The R2 values for simulating leaf, internode, and earhead biomass were 0.62-0.94, 0.74-0.97, and 0.98, respectively, with RMSE values ranging from 0.02 to 0.13 g for leaf biomass, 0.03 to 0.13 g for internode biomass, and 1.71 g for earhead biomass. The results indicated that the model exhibited good performance and reliability in simulating the growth and development of leaves, internodes, and earheads. This provides a solid foundation for the development of a millet model with functional-structural feedback.

摘要
作物生长模型的建立可以模拟环境变化对作物生长的影响，为探索环境因子与作物生长的关系提供理论指导。模型以生长周期(GC)为模拟时间步长，建立了拓扑结构、光合作用、生物量分配和几何形态 4 个子模型。我们定量地利用了有效积温(EAT)的概念，并用库强和扩展率等参数来解释不同器官间的异速生长关系。叶长、叶宽、叶面积、节间体积等几何形态参数的 R^2 值为 0.78 ~ 0.94，回归方程的 f 值为 1533.53 ~ 13949.51。叶片、节间和穗生物量的 R^2 分别为 0.62 ~ 0.94、0.74 ~ 0.97 和 0.98，其中叶片、节间和穗生物量的 RMSE 分别为 0.02 ~ 0.13 g、0.03 ~ 0.13 g 和 1.71 g。结果表明，该模型对叶片、节间和穗的生长发育具有较好的模拟效果和可靠性。这为开发具有功能-结构相互作用的谷子模型提供了结实的基础。

INTRODUCTION
Millet is one of the staple foods grown in Asia, characterized by drought resistance, spine tolerance, and dual use of food and feed. Millet contains abundant dietary fiber and antioxidants, which are beneficial substances for the human body *(Muthamilarasan et al., 2016)*. At present, the genetic improvement of millet varieties is developing continuously, but it still faced the problem of the time-consuming and laborious breeding process *(Kapoor et al., 2022)*. Compared to field experiments, conducting a pre-experiment of crop growth through model simulation allows for earlier detection of potential issues in the experiment, thereby saving labor and financial costs.

Crop models have significant importance in agricultural intelligent decision-making systems, water and nutrient management, yield prediction, and other related areas. The crop growth model is based on light, temperature, water, and other conditions *(Chen et al. Y., 2022; Yu et al., 2022)*, which use computer and mathematical methods to simulate and predict the physiological and ecological processes of crops *(Adam et*

Yuzhi WANG, M.S. Stud. Eng.; Yaoyu LI, M.S. Stud. Eng.; Tengteng QU, M.S. Stud. Eng.; Siyu WANG, M.S. Stud. Eng.; Lili SUN, Ph.D. Eng.; Wuping ZHANG, Prof. Ph.D. Eng.; Fuzhong LI, Prof. Ph.D. Eng..

al., 2013). Most models require the adjustment of numerous parameters to complete the simulation process, and an accurate set of model parameters is an indispensable component of the model.

We have established four sub-models for millet growth and development based on field experimental data. These four models together form a functional-structural plant model for the entire growth cycle of millet. By programming in C++, the distribution and accumulation of biomass is simulated in different organs of millet and quantify the relationships between various parameters in the model. The aim is to construct a functional-structural feedback model for millet growth and development, thereby providing a better understanding of its growth and development processes.

MATERIALS AND METHODS

Field experiment design

Zhangzagu No.10 was used as the research object to conduct a field experiment at the experimental site (112°30'E, 37°26'N) in Wujiapu Village, Taigu District, Jinzhong City, Shanxi Province from May to October 2021. The characteristics of soil basic fertility in the test site are shown in Table 1.

Table 1

Soil nutrient content in the experimental site

Depth (cm)	**Alkali hydrolyzed nitrogen** (g/kg)	**Total nitrogen** (g/kg)	**Total phosphorus** (g/kg)	**Organic matter** (g/kg)
0~20	43.30	1.02	1.13	15.65
20~40	22.10	0.61	0.83	8.19

Data Collection

The morphological indexes of millet were measured manually with a straightedge, vernier caliper, protractor, and other tools, including leaf length, maximum leaf width, Angle between stem and leaf, length and diameter of stem and leaf joint. The growth state of millet plants in different periods was photographed by the digital camera, and leaf curvature and leaf area were extracted by image processing. Meteorological data were obtained from China Meteorological Data Network (http://data.cma.cn/), maximum, minimum and average temperature were used to calculate the daily effective accumulated temperature.

Model construction

Division of basic growth units

The leaf element in the model is the basic structural unit of the model. The internode of the millet and the leaf growing on the node are called leaf metamers *(Zhao et al., 2001)*. The growth interval of each leaf element is called a growth cycle, and the size of the growth cycle is determined by the morphological changes of the millet. The growth and development of millet obey the S-shaped curve. According to the analysis of field experiment data, the model takes the growth cycle as the step length to simulate the whole process of millet growth and development.

The relationship between leaf elements of millet and the effective accumulated temperature was analyzed to predict its growth and development. The effective accumulated temperature was calculated as follows:

$$GDD = \sum (T_{avg} - \mathrm{T}_0) \quad (1)$$

where:

GDD is the calculated effective product (℃ · d), T_{avg} is the daily average temperature (℃), and T_0 is the minimum temperature (℃) required by the growth of millet.

Simulation of geometric form

Suppose that in the N cycle of millet growth, $num(i,t,N)$ is the number of organs with type i and growth age t in millet individuals, and the biomass accumulated by various organs from their generation to the current cycle is $b(i,N)$. Then the geometric characteristics between leaves and nodes were calculated by the allometric change relationship between the cumulative biomass of the organ and the geometric size of the organ *(Zhang W. et al., 2018)*.

Leaf specific weight is one of the important physiological indicators reflecting the morphological characteristics of plant leaves *(Peng et al., 1993)*, and is also an important parameter for the simulation of many ecosystem processes. Leaf area was obtained by multiplying leaf biomass and leaf specific weight (Equation 2).

$$Leaf\_Area(N,i,t) = \frac{Bio(i,N)}{\mathrm{LMA}} \tag{2}$$

where:

$Leaf\_Area(N,i,t)$ is the leaf area (cm^2) in the N cycle. $Bio(i,N)$ is the biomass of leaf i at the N cycle. LMA represents the specific leaf weight of a leaf.

The green photosynthetic area of the internode is obtained by calculating the lateral surface area of the cylinder, which approximates the node as a cylinder. Through the analysis of experimental data, it can be seen that there is a linear relationship between internode surface area and biomass (Equation 3).

$$S_{node} = a * Bio_{node} + b \tag{3}$$

where:

S_{node} represents the photosynthetic area of the internode (cm^2); Bio_{node} is the cumulative biomass of the node; a and b are the parameters of a linear relationship.

Biomass production simulation

The photoresponse model of the rectangular hyperbola was used to describe the photosynthetic rate of green organs such as millet leaves and internodes (Equation 4).

$$P_n = \frac{\alpha \cdot I \cdot P_{max}}{\alpha \cdot I + P_{max}} \tag{4}$$

where P_n is the rate of photosynthesis (μmolCO^2 m^{-2}·s^{-1}); P_{max} is the maximum photosynthetic rate (μmolCO_2 m^{-2}·s^{-1}) in the assimilating organs (leaves and nodes) of millet at light saturation point. I is the photosynthetically active radiation intercepted by photosynthetic organs of millet (J m^{-2} s^{-1}); α is the initial quantum efficiency of the organ (gCO_2 m^{-2}·s^{-1}).

In this study, it is assumed that the organs of millet are not shielded from each other, so the photosynthetic active radiation I intercepted by all the green organs of individual millet is equal (Equation 5).

$$I = PAR \cdot k \cdot (1-r) \cdot exp\big(-k \cdot Surface(i,t,N)\big) \tag{5}$$

where *PAR* is the photosynthetically active radiation reaching the photosynthetic organs of millet (J m^{-2}·s^{-1}).

The calculation method referred to; $Surface(i,t,N)$ is the photosynthesis area of the organ with type i and growth age *t* during the N structural growth cycle. r is the reflectance of green assimilative organs of millet.

The model calculated the PAR of photosynthetic active radiation reaching each green organ at different times of the day based on the latitude and sunshine duration of the crop growing place (Equation 6).

$$PAR = 0.5 \cdot Q \cdot \sin\beta \cdot (1.0 + 0.4 \cdot \sin\beta) \tag{6}$$

$$\sin\beta = \sin\delta\, \sin\varphi + \cos\delta\, \cos\varphi\, \cos\omega \tag{7}$$

where:

β is the altitude Angle of the sun; δ is the declination Angle; φ is the local latitude; ω is the solar hour angle, at the local 12 o 'clock is 0°, increasing 15° every hour; Q is the solar constant (1395 W/m^2).

Gauss three-point integral method was used to calculate the average daily photosynthesis rate of green organs of millet (Equation 8). According to the product of the photosynthesis area of each organ and its photosynthetic rate, the daily photosynthesis products of each organ were calculated.

$$\overline{P_n}(day) = \sum_{h=1}^{3} P_n[th(hh)] \cdot WT(hh) \cdot DL(day) \tag{8}$$

where: DL is day length; $WT(hh)$ is the weight value of the Gauss three-point integral method, and the values are $WT(1)$ =0.2778, $WT(2)$ = 0.4444, $WT(3)$ =0.2778. $\overline{P_n}(\mathrm{day})$ is the daily average daily photosynthetic organs photosynthetic rate (g CO2 m^{-2} s^{-1}).

Dark respiration of leaves and maintenance respiration of other plant organs also consume some photosynthesis products. The assimilation products consumed through daily maintenance growth activities of millet can be obtained by multiplying the newly added assimilate yield and the maintenance consumption coefficient of organs (and temperature correction coefficient). The growing consumption of each organ can be obtained by multiplying the newly added assimilate yield by the photorespiration consumption coefficient (and temperature correction coefficient) of the organ. Finally, the net assimilation amount was multiplied by the conversion coefficient to obtain the added biomass of millet under different growth cycles.

Biomass allocation simulation

Photosynthetic production accumulates to obtain the newly generated biomass for each growth cycle, and then each organ competes for the newly generated biomass based on the product of its sink strength and expansion rate, obtaining the biomass obtained by different types of organs at different growth stages (Equation 9). On this basis, the biomass obtained by the same organ in different growth cycles was accumulated to obtain the cumulative biomass value of the organ in different growth cycles, as shown in Equation 10:

$$\Delta b(i,t,N) = \frac{Sink(i)\cdot f(i,t)\cdot Q(N)}{\sum_i \sum_{t=1}^{N} num(i,t,N)\cdot Sink(i)\cdot f(i,t)} \tag{9}$$

$$b(i,N) = \sum_{i=1}^{N} \Delta b(i,t,N) \tag{10}$$

where:

$\Delta b(i,t,N)$ is the biomass (g) obtained by the organ type i and growth age t in the N growth cycle; $num(i,t,N)$ is the number of organs with type i and growth age t contained in the individual plant in the N growth cycle, which was obtained by the aforementioned millet structure module. $Sink(i)$ is the parameter of leaf metamers; $Q(N)$ is the available biomass of plants in the N^{th} growth cycle (g). $b(i,N)$ is the cumulative biomass obtained by an organ of type i in the N growth cycle (g).

The growth rate of various organs is characterized by the change rate of biomass during their growth and described by a normalized beta distribution curve (Equation 12), which involves three parameters related to organ types, namely $a(i)$, $b(i)$ and $T(i)$. The first two parameters control the shape of the curve. The third parameter represents the maximum number of expansion cycles of the biomass obtained from the growth of different organs. $a(i)$, $b(i)$ and $T(i)$ of various organs were obtained by analyzing the biomass changes of organs in different cycles.

$$f(i,t) = \frac{g(i,t)}{M}(1 \le t \le T(i)) \tag{11}$$

$$g(i,t) = (t-0.5)^{a(i)-1}\cdot(T(i)-t+0.5)^{b(i)-1} \tag{12}$$

$$M = \sum_{t=1}^{T(i)} g(i,t) \tag{13}$$

RESULTS AND ANALYSIS

Model Parameters

The parameters in the model can be divided into four categories: structural parameters, morphological parameters, photosynthetic parameters, and biomass allocation parameters. The structural parameters of the model can be determined by accumulated temperature. The effective accumulated temperature of millet from seedling emergence to mature harvest was 1489℃ day, and its development situation was shown in Fig. 1 (from heading stage to maturity stage, the number of leaf elements of millet did not change, and some of the generated organs would continue to grow. According to the relationship between leaf elements and accumulated temperature, the growth cycle calculated by accumulated temperature was used to describe the growth of millet).

According to its growth rate, one leaf element can be generated by the main stem of millet every accumulated temperature of 36.9℃ day. Therefore, the heat time of 36.9℃ day was defined as the growth cycle of a millet and expressed by variable N, so millet experienced 40 growth cycles in total. The effective accumulated temperature of millet from emergence to heading was about 800.5℃ day, so the millet went through 22 cycles before heading.

In the model, leaf Ⅰ, leaf Ⅱ, leaf Ⅲ were divided into three different types according to the different maximum expansion cycle (survival growth cycle) of each organ, so as to obtain seven different organs, namely leaf Ⅰ, leaf Ⅱ, leaf Ⅲ, node Ⅰ, node Ⅱ, node Ⅲ and earhead (Table 2). Meanwhile, for the sake of description, the first leaf and node that begins to grow is called leaf 1 or node 1, the second leaf and node is called leaf 2 or node 2, and so on to leaf 22 or node 22.

Table 2

Division of millet organs

	Leaf Ⅰ	Leaf Ⅱ	Leaf Ⅲ	Node Ⅰ	Node Ⅱ	Node Ⅲ	Earhead
Cycles	1-7	8-17	18-22	1-7	8-17	18-22	22-40
Maximum cycle	15	20	25	15	20	25	18

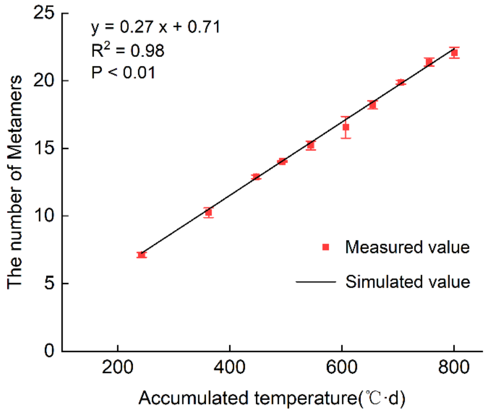

Fig. 1 - Effective accumulated temperature and number of Metamers

On this basis, through the operation of the model, the difference between simulated and measured values in each cycle was compared, and then the parameters were adjusted so that when the difference between simulated and measured values of biomass was less than 10%, the parameters were used as biomass production parameters in this study. The photosynthetic parameters of the organs were given based on the experimental data (Table 3).

Table

Model photosynthetic parameters

Symbol	Value	Parameters
P_{max}	37μ mol $CO_2 \cdot m^{-2} \cdot s^{-1}$	Maximum photosynthetic rate of a single organ
r	0.24	Blade reflectance
φ	37°	Latitude of test site

Based on the method described in section 2.3.3, the preset initial values were put into the model and the parameters of library strength and expansion rate of each organ of millet were obtained by gradient descent method, as shown in Table 3. From the perspective of different organs, the pool strength and expansion rate of leaves and internodes ranged from 0.01 to 0.08, 1.28 to 2.77 and 3.39 to 4.97, respectively, and the pool strength of leaves was greater than that of internodes. The distribution parameters of leaves would gradually decrease with the generation time (type change), and the expansion rate of internodes a tended to decrease with the generation time. The biomass allocation parameters of ear were different, and the reservoir strength and spread rate reached 5.57, 3.31 and 4.22, respectively. It is worth noting that the pool strength of ear is two orders of magnitude different from that of leaf and internode, and the expansion rate is also larger than that of leaf and internode.

Table 4

Biomass allocation parameters during millet growth

Type	Sink	Expand a	Expand b
Leaf Ⅰ	0.08	1.28	4.97
Leaf Ⅱ	0.03	1.48	4.13
Leaf Ⅲ	0.04	1.79	3.39
Node Ⅰ	0.02	2.77	3.43
Node Ⅱ	0.01	1.30	4.11
Node Ⅲ	0.02	0.73	3.53
Earhead	5.57	3.31	4.22

Parameter sensitivity analysis

This paper refers to the sensitivity analysis method of Zhang Ni et al. *(C. Zhang et al., 2019)*, and takes the photosynthetic parameters proposed in 3.1 (P_{max} =37, φ=37, r = 0.24) and changes each parameter by ±10% and ±30%, respectively. According to Formula 3, the dynamics change of cumulative biomass corresponding to the changes of different parameters in a given growth cycle were calculated, and the results were shown in Figure 2.

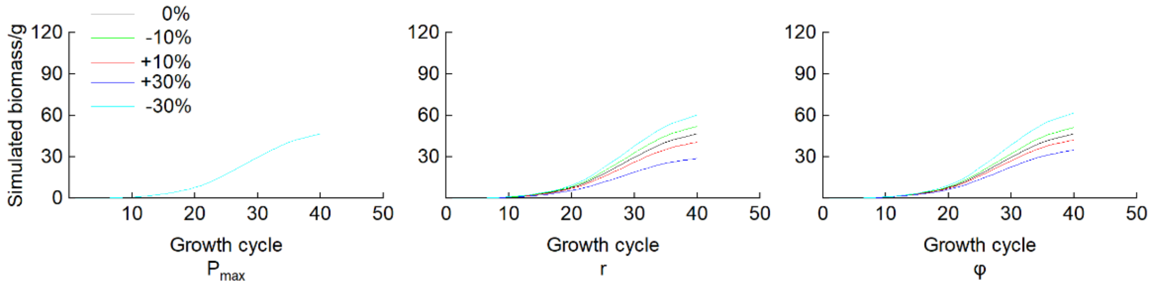

Fig. 2 - The impact of model parameter changes on biomass under different cycles

when:

P_{max} changes by ±10% (±30%), the variation range of biomass is always within 1%. The reflectance *r* and latitude *φ* have great influence on the biomass, and the influence degree gradually increases with the increase of the growth cycle. When *r* and *φ* vary by ±10% (± 30%), the biomass varies by ±10% (±33%) and ±13% (±38%), respectively. In general, the biomass simulated by this model is not sensitive to P_{max}, but more sensitive to *r* and *φ*.

Geometric form model simulation

The relationship between leaf length, leaf width, leaf area, internode volume, ear length and biomass of millet was analyzed, and the morphological structure parameters of millet organs and biomass were obtained, and the morphological structure model of millet was built. The geometric shape model of millet leaves is in Table 5. The R^2 values between biomass and leaf length, leaf width, leaf area, internode volume and ear length were 0.82, 0.78, 0.94, 0.82 and 0.89, respectively. The F value of the regression equation was between 69.09 and 3030.11, which proved the established model was valid and could be applied to the simulation of morphological parameters of various organs of millet.

Table 5

Parameters of millet morphological structure model

Parameter type	Regression equation	R^2	F
Leaf length	$y = 56.43 \cdot x^{0.44}$	0.82	1533.53
Leaf width	$y = 3.79 \cdot x^{0.38}$	0.78	2378.91
Leaf area	$y = 132.62 \cdot x$	0.94	13949.51
Node volume	$y = 8.19 \cdot x$	0.82	3030.11
Earhead length	$y = 3.84 \cdot \ln(x) + 17.93$	0.89	69.09

Biomass production model simulation

The photocontracting parameters listed in Table 4 were used to simulate the total biomass accumulated during each cycle of millet growth (Fig.3).

As can be seen from Figure 3, biomass accumulation basically accords with the "S" shaped curve of crop growth, and the determination coefficient R^2 and RMSE between simulated and measured values reached 0.95 and 4.48 g, indicating that the model can well describe above-ground biomass production of millet.

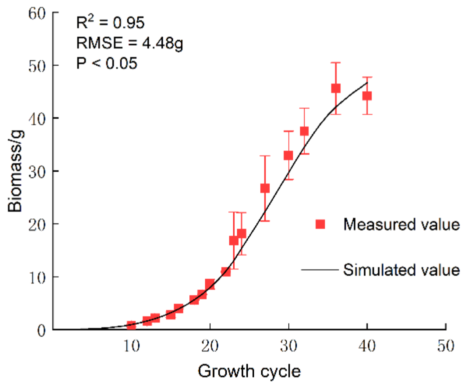

Fig. 3 - Comparison between measured and simulated values of millet biomass

Biomass allocation model simulation

Biomass allocation is a key component of the functional structural feedback mechanism and also a key component in constructing functional structural plant models. Based on the parameters obtained in the above biomass allocation model, the biomass of millet under 15 different leaf positions (leaf 7-leaf 21) was simulated, and the simulated values were compared with the measured values, as shown in Fig. 4. From the perspective of individual organs, the coefficients of determination R^2 between simulated values and measured values for 15 different leaf positions ranged from 0.62-0.94, and RMSE ranged from 0.03 g to 0.13 g. The simulation results of the middle part of 7-leaf 17 were more similar to the measured values, and the RMSE values were all less than 0.09 g.

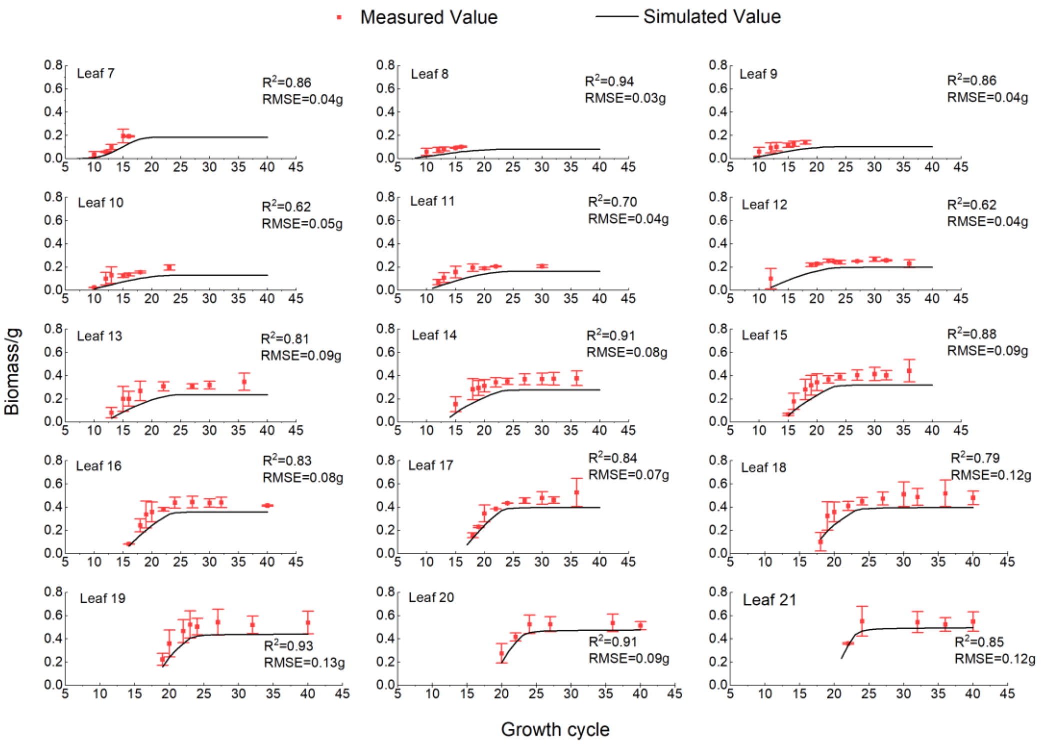

Fig. 4 - Comparison of simulated and measured cumulative biomass of different leaf positions in each cycle

The model simulated the biomass of millet under 15 different internodes (nodes 7-21), and compared the simulated value with the measured value. The results are shown in Fig.5.

As can be seen from the figure, the coefficient of determination R^2 of the simulated value and the measured value between 15 different nodes ranges from 0.74 to 0.97, and the RMSE ranges from 0.04 g to 0.12 g.

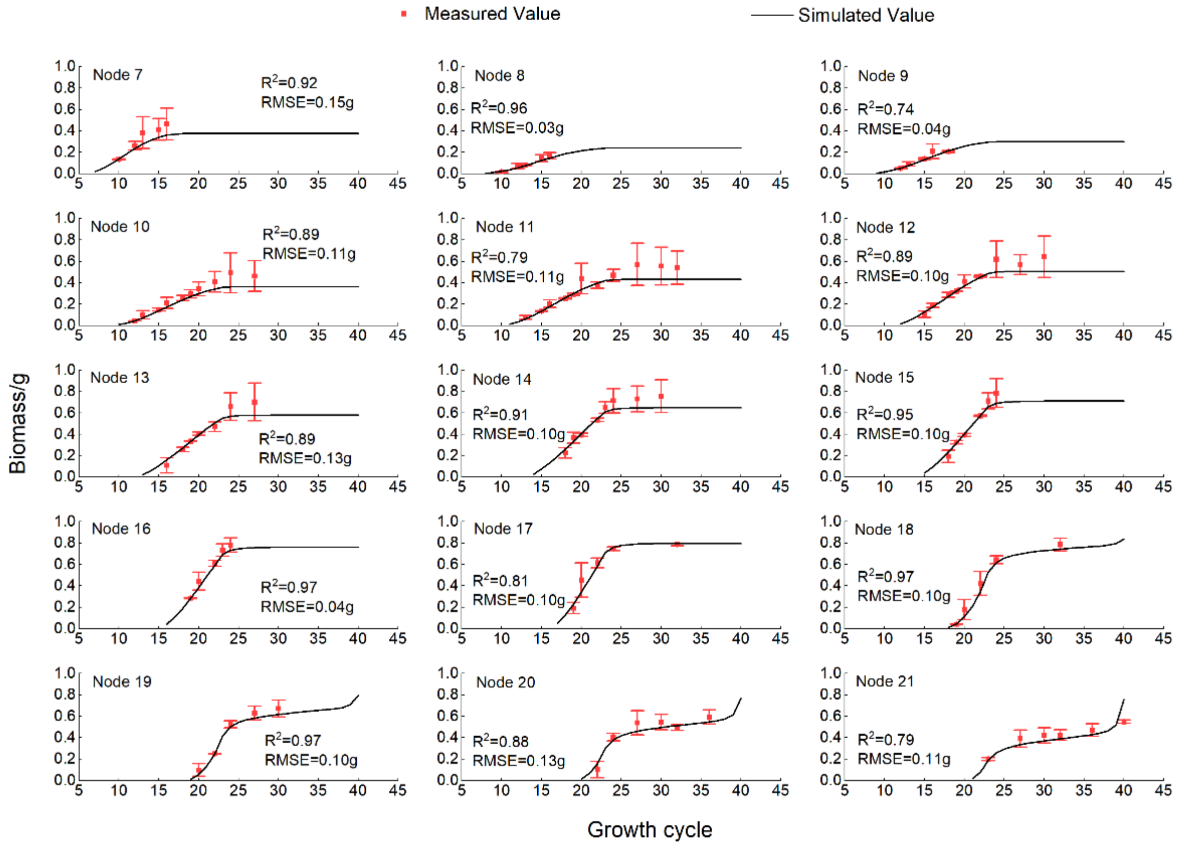

Fig. 5 - Comparison of simulated and measured cumulative biomass at different nodes and periods

The biomass of earhead is very important to yield *(Stein et al., 1997)*. The cumulative biomass of ear in each cycle is shown in Fig. 6. After the 22nd cycle, the proportion of new biomass allocated from millet plants to ear gradually increased, and reached the highest point around the 40th cycle. From the perspective of millet as a whole, the allocation of new biomass of whole millet plant after the 22nd cycle was significantly more inclined to ear. It can be seen from the figure that the simulated value is in high consistency with the measured value. The coefficient of determination R^2 reached 0.98 and the RMSE value was 3.17 g. It shows that the model has certain applicability.

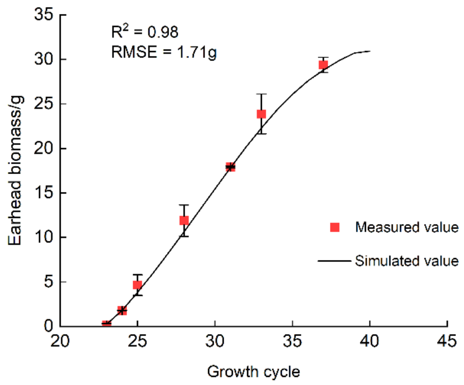

Fig. 6 - Comparison of simulated and measured cumulative biomass in each period of spike

Model verification

The first 5 samples of the experiment were used to build the model, and the last 5 samples were used to verify the biomass allocation results of the model. The accuracy of measured and simulated values is shown in Table 5. The root mean square errors of different leaf, stem and ear types were 0.03-0.11 g, 0.11-0.15 g and 1.71 g, respectively. The results showed that the model could be applied to simulate the growth of millet organs.

Table 6

Comparison between simulated and measured values of the model

Type	RMSE	MRE / %
Leaf Ⅰ	0.03	15.46
Leaf Ⅱ	0.06	20.67
Leaf Ⅲ	0.11	19.76
Node Ⅰ	0.15	26.79
Node Ⅱ	0.11	20.4
Node Ⅲ	0.07	16.7
Earhead	1.51	12.74

DISCUSSION

Under different cycles, photosynthetic parameter r affects the intercepted light and effective radiation (Equation 4), while latitude φ affects the photosynthetically active radiation reaching the leaves (Equation 7). Therefore, φ and r have a great influence on crop biomass, which is similar to the research results of *(J. Chen et al., 2018)*. Reflectance r is an important parameter to measure the photosynthetic performance of crops. It is important for the formation of the photosynthetic rate and biomass of leaves *(Luo et al., 2022)*. The maximum photosynthetic rate P_{max} had little effect on biomass simulation.

The geometric form model had a great influence on the simulation results of millet biomass, which was similar to the research results of *(Guo & Fritschi, 2020; Li et al., 2011)*, model comparing the relationship between leaf weight and biomass. The model simulated the morphological changes of various organs of millet, and the geometric morphological model built by this model had high simulation accuracy for leaf length, leaf width, leaf area, and internode volume of millet.

The simulation process of the photosynthesis of millet was simplified by using the Gaussian integral method. However, during the actual growth and development of crops, the light absorbed and reflected by different canopy layers was significantly different, and the fluctuation degree of the light environment of the lower leaves was greater than that of the upper leaves*(Ting et al., 2021)*. In the future, the accuracy of model simulation can be further improved by refining the accurate distribution of canopy illumination.

CONCLUSIONS

By analyzing the effective accumulated temperature, light and other environmental factors of millet growth, its growth model was established, which can be used to quantify the influence of different environmental factors on the growth and development process of millet, providing a scientific method for studying its growth and development law, and providing a theoretical basis for further exploring the relationship between its growth and the environment.

ACKNOWLEDGEMENT

The authors were funded for this project by the Major research and development Projects of Shanxi Province, China (2022ZDYF127), and the Basic Research Project of Shanxi Province (202103021224123).

REFERENCES

[1] Adam M., Wéry J., Leffelaar P. A., Ewert F., Corbeels M.,Van Keulen H. (2013). A systematic approach for re-assembly of crop models: An example to simulate pea growth from wheat growth. *Ecological modelling,* Vol. 250, 0304-3800. pp. 258-268. 10.1016/j.ecolmodel.2012.10.012

[2] Chen J., Chen S., Zhang Z., Fu Q., Bian J.,Cui T. (2018). Investigation on photosynthetic parameters of cotton during budding period by multi-spectral remote sensing of unmanned aerial vehicle. (无人机多光谱遥感反演花蕾期棉花光合参数研究). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 10, pp. 230-239. 10.6041/j. issn. 1000-1298.2018.10.026

[3] Chen Y., Chu C., He F.,Fang S. (2022). A mechanistic model for nitrogen-limited plant growth. *Annals of Botany,* Vol. 129, 0305-7364. pp. 583-592. 10.1093/aob/mcac018

[4] Guo Y.,Fritschi F. B. (2020). Influence of manganese availability on switchgrass and pearl millet biomass production. *Crop science,* Vol. 61, pp. 643-656. 10.1002/csc2.20310

[5] Kapoor C., Singh S. P., Sankar S. M.,Singh N. (2022). Enhancing drought tolerance in pearl millet

(Pennisetum glaucum L.): integrating traditional and omics approaches. *Euphytica,* Vol. 218, 0014-2336. pp. 104. https://doi.org/10.1007/s10681-022-03045-5

[6] Li X., Pan Z., Upadhyaya S., Atungulu G.,Delwiche M. (2011). Three-dimensional geometric modeling of processing tomatoes. *Transactions of the Asabe,* Vol. 54, pp. 2287-2296. 10.13031/2013.40642

[7] Luo J.-F., Xie C.-Q., Pan S.-L., Tang C.-L., Chen W., Yi H.-L., et al. (2022). A study of the spectral reflectivity of the osmanthus tree leaf and its spectral properties. *Journal of Quantitative Spectroscopy and Radiative Transfer,* Vol. 287, 0022-4073. pp. 108-228. 10.1016/j.jqsrt.2022.108228

[8] Muthamilarasan M., Dhaka A., Yadav R.,Prasad M. (2016). Exploration of millet models for developing nutrient rich graminaceous crops. *Plant Science,* Vol. 242, 0168-9452. pp. 89-97. 10.1016/j.plantsci.2015.08.023

[9] Peng S., García F., Laza R. C.,Cassman K. G. (1993). Adjustment for Specific Leaf Weight Improves Chlorophyll Meter's Estimate of Rice Leaf Nitrogen Concentration. *Agronomy journal,* Vol. 85, pp. 987-990. https://doi.org/10.2134/agronj1993.00021962008500050005x

[10] Stein A., Brouwer J.,Bouma J. (1997). Methods for comparing spatial variability patterns of millet yield and soil data. *Soil Science Society of America Journal,* Vol. 61, pp. 861-870. https://doi.org/10.2136/sssaj1997.03615995006100030021x

[11] Ting Z., Huixing K., Xinran K.,Yan Z. (2021). Dynamics of Photosynthetic Active Radiation and Photosynthetic Characteristics of Rice Leaves at Two Canopy Heights. (水稻冠层不同高度光合有效辐射动态与叶片光合作用特性研究). *Acta Scientiarum Naturalium Universitatis* Vol. 57, 0479-8023. pp. 723-732. 10.13209/j.0479-8023.2021.046

[12] Yu L., Liu Y., Liu T., Yu E., Bu K., Jia Q., et al. (2022). Coupling localized Noah-MP-Crop model with the WRF model improved dynamic crop growth simulation across Northeast China. *Computers and Electronics in Agriculture,* Vol. 201, 0168-1699. pp. 107-123. 10.1016/j.compag.2022.107323

[13] Zhang C., Ju X., Powlson D. S., Oenema O., Smith P.,Powlson D. (2019). environmental processes nitrogen surplus benchmarks for controlling n pollution in the main cropping systems of china nitrogen surplus benchmarks for controlling n pollution in the main. *Environmental Science & Technology,* Vol. 53, pp. 6678-6687. 10.1021/acs.est.8b06383

[14] Zhang W., Wang G., Han J., Li F., Zhang Q.,Doonan J. (2018). *A functional-structural model for alfalfa that accurately integrates shoot and root growth and development.* Paper presented at the 2018 6th International Symposium on Plant Growth Modeling, Simulation, Visualization and Applications (PMA).

[15] Zhao X., Reffye P. D., Xiong F. L., Hu B. G.,Zhan Z. G. (2001). Dual-scale automaton model for virtual plant development (虚拟植物生长的双尺度自动机模型). *Chinese Journal of Computers,* Vol. 24(6), pp.608-615