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RESEARCH

Calibration and validation of APSIM for maize grown in different seasons in Southwest tropic of China

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ABSTRACT

In order to estimate the adaptability of Agricultural Production Systems Simulator (APSIM)-Maize model under the special climate environment in tropic, 10 field experiments were conducted at different seasons in three sites (Longchuan, Mangshi and Ruili) of tropic in Yunnan Province, China. The parameters of APSIM model were calibrated and its adaptability was validated. The results showed that the days from sowing to flowering and sowing to maturity were predicted accurately for all sites with mean errors of 2.0 ± 0.4, and 3.2 ± 0.7 d respectively. The normalized root mean square errors (NRMSE) of the model for yield prediction were 2%, 3% and 5% for each of three sites, respectively, which indicated that the APSIM model had good accuracy and sensitivity in predicting phenological phases and yield of maize (*Zea mays* L.) grown in different seasons, and the model had good adaptability in the tropic of Southwest China. This study provided the basis and technical support for evaluating maize production potential based on the model.

Key words: APSIM, calibration and validation, crop simulation, maize, *Zea mays*.

INTRODUCTION

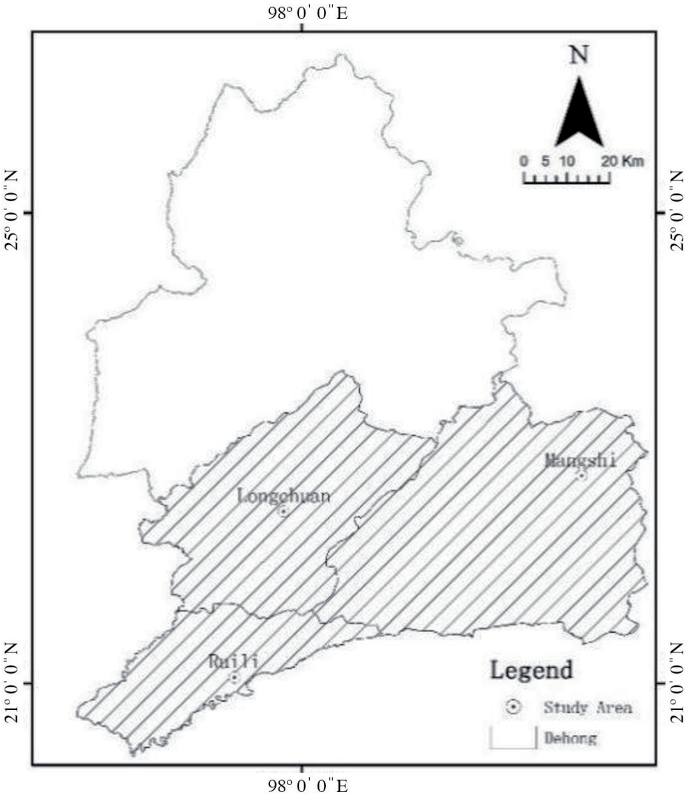
Maizeis (*Zea mays* L.) is one of the most widely distributed crops in the world, ranking third only to wheat and rice in terms of total yield and planting area. The Southwest is a significant grain producing region in China. Among them, winter sowing maize in tropical areas is an important supplement to maize production. Maize is the largest grain crop in Yunnan Province. In 2019, the farm land in Yunnan Province covered about 6938.86 thousand hectares, in which 1782.4 thousand hectares, accounting for about 15%, was covered by maize. Based on the field experiment in this region, the research on maize simulation is of great practical significance for scientific zoning of industrial layout and accurate decision-making of production management.

Crop simulation research began in 1960s. Maize is one of the earliest crops in crop growth models. The Dutch De Wit School first created Wageningen model, which studied the solar syndication rate of maize single leaf canopy and simulated it on computer. By the 1970s, studies have established a simulation model of the effect of leaf area and blade angle on photosynthesis of maize group, which promoted the further development of the maize crop model, maize and physical development of different canopy photosynthesis, leaf, stem, root growth, breathing loss, DM accumulation, and the distribution of the net photosynthetic product and a series of process is included. Compared with traditional statistical analysis methods, crop model research can more accurately express the relationship between crop growth and various factors, which has obvious advantages in assessing the impact of climate change on crop growth and yield, and has become an efficient tool to assist agricultural production decision-making at present (Shen et al., 2002; Lin et al., 2003).

The application test of crop model in different regions is a significant content of simulation research. Foreign scholars have applied CERES Maize model to test in India, West Africa, Nigeria, Belgium and Chile (Lizaso et al., 2003; Lizaso et al., 2005; Angevin et al., 2007), and debugged the model based on the experimental data, which improves the adaptability of the model in different regions. There are abundant researches on the test and application of maize growth model in China, and the parameter calibration and validation researches has been carried out in many regions, but it has not been widely used. The Agricultural Production Systems Simulator (APSIM) model mainly focuses on the study of adaptation in North China Plain (Wang et al., 2007; Chen et al., 2009; Li et al., 2009; Wang et al., 2015; Zhang et al., 2018; Zhao et al., 2018), Northeast China (Liu et al., 2012; Lü et al., 2013; Li, 2017; Huang et al., 2020) and Loess Plateau (Zhou, 2008; Zhang et al., 2019; Ali et al., 2021; Sun et al., 2021; Wang et al., 2021). CERES-Maize model has been tested in Loess Plateau (Zou and Feng, 2014), Huang-Huai Plain (Li et al., 2013), North China Plain (Dai et al., 2009) and Northeast China (Pang et al., 2014). The test of EPIC Model in North China Plain (Fan et al., 2014); the test of CropSyst in Song-Nen Plain (Wang et al., 2005); the test of GECROS Model in Huang-Huai-Hai area (Wu et al., 2015).

There are also studies to test the major maize planting regions in China (Hu et al., 2008; Xiong and Lin, 2009). However, the research is mainly concentrated in the north planting area, but the research on the maize growth model in the southwest area is less, and the research on the maize growth model in the tropical southwest of China has not been reported. Because of the special climatic environment and light and heat resources in the southwest tropical region, winter sowing and summer sowing maize exist simultaneously in this area, especially the climatic conditions in the growth period of winter sowing maize in tropics are quite different from those in other regions, which is of great significance for verifying the universality of APSIM model in this area. Based on 10 field experiments conducted in winter and summer in three sites of tropical regions in Yunnan Province (Figure 1), this study calibrated and validated the parameters of APSIM model, evaluated the adaptability of APSIM model in maize in Yunnan, and provided theoretical basis for further study of maize production potential in this region under the background of global climate change in the future.

Figure 1. Location of the study sites, Longchuan, Ruili, and Mangshi.



MATERIALS AND METHODS

Overview of study area

The field experiment of this study was set up in Longchuan (24°2’ N, 97°79’ E), Mangshi (24°4’ N, 98°59’ E) and Ruili (24°1’ N, 97°85’ E), southern part of Yunnan Province, China, main producing area of winter sowing maize (*Zea mays* L.) The average annual temperature in the whole area is 18 ~ 21 °C, average annual precipitation is 1400 ~ 1800 mm, and sunshine duration is 2100 ~ 2300 h. The evaporation is greater than the precipitation, the seasonal drought problem is prominent, relative humidity is about 80%, according to the Food and Agriculture Organization (FAO) soil classification system, its main soil type is the lateritic red soil, and the climatic conditions in each planting area is favorable. It belongs to the subtropical monsoon climate in South Asia with sufficient light, abundant rainfall, obvious three-dimensional climate and inversion temperature layer, which provides excellent climatic conditions for high and stable yield of maize.

Experimental settings and data sources

The meteorological data of each meteorological station comes from the Scientific Data Sharing Network (http://cdc.cma.gov.cn), including daily maximum temperature, minimum temperature, including daily maximum temperature, minimum temperature, average temperature, sunshine hours, daily precipitation and average relative humidity. Penman-Monteith formula (Keating et al., 2003) is used to calculate the total solar radiation value required by the model.

Soil data come from agrometeorological observatory, Chinese Soil Species Records and Chinese Soil Science Database, including layered soil bulk density, wilting water content, field water holding capacity, saturated water content and soil organic C, etc. Soil data and years correspond to crop data. Table 1 presents soil basic physical characteristics parameters of test stations.

Crop data come from the data of 10 field experiments in Longchuan and Ruili in 2010-2012, 2013-2014 and Mangshi in 2019-2020 (Table 2). The 10 experiments have obvious environmental differences due to different sites and sowing dates, among which the lowest and highest average temperature in all phenological phases were 16.3 and 26.7 °C, respectively, and the lowest and highest precipitation values were 58 and 1267 mm, respectively. The experimental data collected include maize varieties, sowing density, sowing row spacing, sowing depth, sowing date, fertilization type, fertilization time, fertilization amount, specific irrigation measures, main phenological phases (seedling phase, flowering phase and mature phase) and yield.

Table 1. Basic physical characteristic parameters of soil from stations.

Depth	Bulk density	Field capacity	Wilting water content	Saturated water content
cm	g cm^{-3}	mm^3 mm^{-3}	mm^3 mm^{-3}	mm^3 mm^{-3}
0-20	1.34	0.44	0.25	0.53
20-40	1.32	0.48	0.26	0.55
40-60	1.31	0.51	0.28	0.58
60-100	1.31	0.51	0.28	0.58

Table 2. Maize field test setting with multiple varieties and pilot projects.

Sites	Experiment	Sowing season	Variety	Sowing date	Average daily temperature of growth period	Rainfall of growth period
					℃	mm
Longchuan	I	2010 Winter	Huidan4, Deyu6	17 Nov, 8 and 29 Dec in 2010	18.41, 20.27, and 17.66	434, 361, and 400
	II	2011 Winter	Huidan4, Deyu6	28 Nov, 18 Dec in 2011 and 7 Jan in 2012	18.03, 18.54 and 17.76	60, 58 and 67
	III	2013 Winter	Huidan4, Deyu6	11 and 31 Dec in 2013	17.84, and 18.62	81.7 and 116
	IV	2014 Summer	Huidan4, Deyu6	1st May, 16 May, and 1st Jun in 2014	25.16, 25.43 and 25.18	783, 815 and 855
Ruili	V	2010 Winter	Deyu6	16 Nov, 7 and 28 Dec in 2010	17.31, 18.48 and 16.33	221, 325 and 279
	VI	2011 Winter	Deyu6	28 Nov, 18 Dec in 2011, and 7 Jan in 2012	19.42, 19.89 and 18.75	68, 65 and 69
	VII	2013 Winter	Deyu6	11 and 31 Dec in 2013	19.69 and 20.38	83 and 90
	VIII	2014 Summer	Deyu6	1st May, 16 May, and 1st Jun in 2014	26.49, 26.76, and 26.55	775, 733 and 772
Mangshi	IX	2019 Spring	Yunrui505	8 and 28 Apr and 17 May in 2019	24.50, 25.06 and 25.48	646, 1061 and 1267
	X	2020 Summer	Yunrui505	8 and 28 May, and 21 Jun in 2020	24.70, 24.88 and 25.05	1251, 1266 and 1012

APSIM model

Agricultural Production Systems Simulator (APSIM) is a mechanism model for simulating the physical process of agricultural production system developed by Agricultural Production Systems Research Unit (APS-RU), which belongs to Commonwealth Scientific and Industrial Research Organization (CSIRO) and Queensland government, Australia. It has a good effect in simulating the growth and development, yield and water use efficiency of crops under the influence of climate change, and has been widely used in the production of many countries and areas around the world. The main core modules of APSIM model include soil module, management module and crop module. The model is centered on the soil environment in which crops grow, and is divided into modules such as soil N, soil P and surface stubble to simulate soil water movement and nutrient transfer. Soil water characteristic parameters include field capacity (mm^3 mm^{-3}), wilting coefficient (mm^3 mm^{-3}) and saturated water content (mm^3 mm^{-3}) of layered soil. The management module is mainly used for setting parameters of fertilization and irrigation management measures, sowing and harvesting crops, calling each module, setting input and output modules, etc. And the daily meteorological data needed by the model include daily maximum temperature (°C), daily minimum temperature (°C), precipitation (mm) and total radiation ($MJ\ m^{-2}\cdot d^{-1}$). The main outputs of the model include the key phenological phases (seedling stage, flowering stage and maturity stage) and yield of crops. Crop module mainly simulates the physiological development time of crops, the interaction between crops and soil during growth and the formation of yield. The physiological development period of crops is simulated by temperature and photoperiod response function, leaf area growth and senescence are expressed as functions of temperature, and crop water absorption is based on root water absorption function (Junior et al., 2021).

Model parameter calibration and verification

The field experiment data are divided into two groups, among which the data of experiments I, II, V, VI and IX are used for parameter adjustment; The data of the other five experiments data are used to verify the model and evaluate its adaptability. The maize parameters of model adjustment include accumulated temperature from emergence to end of juvenile, accumulated temperature from end of juvenile to floret differentiation, accumulated temperature from flowering to grain filling, accumulated temperature from flowering to maturity, photoperiod slope, potential grain filling rate, maximum grain per head, etc. (Table 3).

During parameter calibration and validation, the applicability of APSIM model is evaluated by comparing the simulated value with the measured value by 1:1 graph and various evaluation indexes. The following statistical indicators are used: root mean square error (RMSE) between simulated and measured values, normalized root mean square error (NRMSE), coefficient of determination (R^2) and consistency index (D). The R^2 and D can reflect the consistency between the simulated value and the measured value, and the closer their value is to 1, the better the simulation effect of the model; RMSE and NRMSE can reflect the relative error and absolute error between the simulated value and the measured value. The smaller the RMSE and NRMSE, the better in accuracy of the model.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - X_i)^2}{N}} \tag{1}$$

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Y_i - X_i)^2}{N}}}{\bar{X}} \times 100\% \tag{2}$$

$$R^2 = \frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}{\sum_{i=1}^{N}(X_i - \bar{X})^2} \tag{3}$$

$$D = 1 \frac{\sum_{i=1}^{N}(Y_i - X_i)^2}{\sum_{i=1}^{N}\left(\left|Y_i - \bar{X}\right| + \left|X_i - \bar{X}\right|\right)^2} \tag{4}$$

Where, Y_i is the simulated values; X_i is the measured values; $\bar{X}$ is the measured average value; $\bar{Y}$ is the simulated average value; N is the number of samples.

Table 3. Genetic parameters for different varieties of winter maize at three sites in the study area.

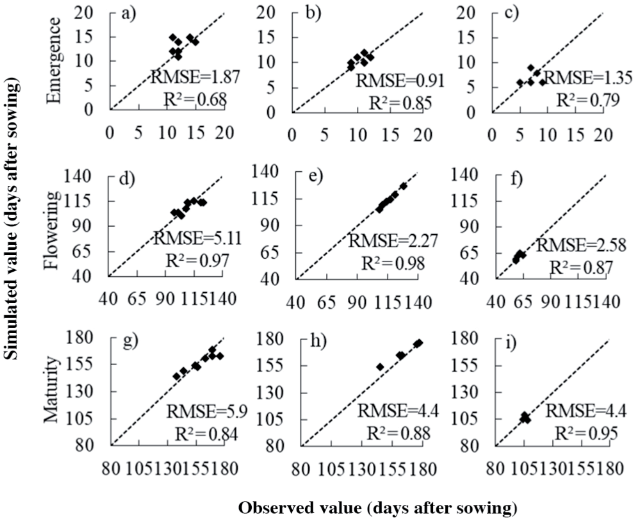
Variety	Accumulated temperature from emergence to end of juvenile	Accumulated temperature required from flowering to maturity	Photoperiod slope	Potential filling rate	Maximum-grain per head
	°C d	°C d	°C h^{-1}	mg $grain^{-1}$ d^{-1}	
Huidan4	360	990	23.0	9.0	600
Deyu6	340	980	23.0	9.0	650
Yunrui505	310	950	23.0	9.5	650

RESULTS AND DISCUSSION

Phenological phases

Due to the different experimental sites and sowing dates, there are certain differences in the phenological phases. The average of phenological phases was 9.8 ± 0.6 d from sowing to seedling emergence, 99.1 ± 5.5 d from sowing to flowering, and the whole phenological phase was 143.5 ± 6.6 d. The whole phenological phase of Longchuan experiment is obviously longer than other experiments, and the whole phenological phase of winter sowing maize is longer than that of summer sowing maize. The simulated values of the three periods were 10.4 ± 0.7 d for seedling emergence, 102.7 ± 5.3 d from sowing to flowering, and 145.9 ± 6.4 d for the whole growth period. From the comparison between the simulated values and the measured values (Figure 2), the simulated values and the measured values basically fall near the 1:1 line, and the prediction effect of the model is good. The total error of all the test data is 2.5 ± 0.3 d (n = 23), among which the prediction error of flowering period is 2.0 ± 0.4 d (n = 8) and that of mature period is 3.2 ± 0.7 d (n = 8). The comparison of different sites shows that the error of Longchuan is higher than the other two sites, and the error of Longchuan experiment is also larger, which mainly appears in the experimental treatment with long phenological phase or growth period. The experimental error in Mangshi area is obviously small, which is related to the short phenological phase in summer. Considering that RMSE value is related to the value of participating statistics, this study compares NRMSE, R^2 and D values at the same time. From the comparison of NRMSE (Table 4), the error difference among the three sites is not big, and the NRMSE of the whole growth period is less than 5%, which is accurate. This study also analyzed the D value and R^2 value predicted by the model (Table 4), and the results showed that the overall prediction accuracy is high, and

Figure 2. Comparison between simulated and measured development stages for different varieties of maize at three stations in Dehong.



a, b and c are the comparison between the measured and simulated values of different varieties of emergence at three stations of Longchuan, Ruili and Mangshi; d, e, and f are the comparison between the measured and simulated values of different varieties of flowering at three stations of Longchuan, Ruili and Mangshi; g, h and i are the comparison between the measured and simulated values of different varieties of maturity at three stations of Longchuan, Ruili and Mangshi. The dashed diagonal line is 1:1 line and insets are the values of RMSE, R^2.

Table 4. Validation results of APSIM model at three stations.

		Validation			
Sites	Item	R^2	D	RMSE	NRMSE
Longchuan	Days from sowing to emergence	0.68	0.79	1.87	10%
	Days from sowing to flowering	0.97	0.84	5.11	5%
	Days from sowing to maturity	0.84	0.91	5.9	3%
	Yield, kg hm^{-2}	0.87	0.92	210.83	2%
Ruili	Days from sowing to emergence	0.85	0.87	0.91	8%
	Days from sowing to flowering	0.98	0.97	2.27	2%
	Days from sowing to maturity	0.88	0.95	4.4	8%
	Yield, kg hm^{-2}	0.88	0.88	289.46	3%
Mangshi	Days from sowing to emergence	0.79	0.81	1.35	10%
	Days from sowing to flowering	0.87	0.85	2.58	5%
	Days from sowing to maturity	0.95	0.82	4.44	4%
	Yield, kg hm^{-2}	0.89	0.90	524.79	5%

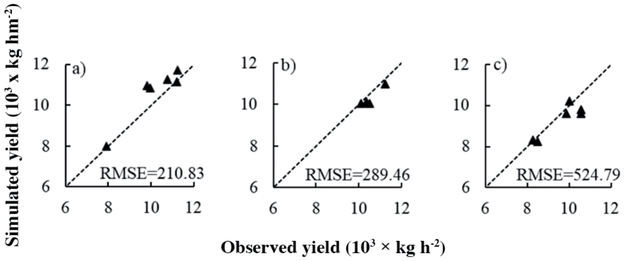
R^2: Coefficient of determination; D: consistency index, RMSE: root mean squared error, NRMSE: normalized root means square error.

the prediction results in different areas had little difference. The measured and simulated days of the three phenological phases were 0.81, 0.92 and 0.89 respectively, the NRMSE were 9%, 4% and 5% respectively, the NRMSE were all lower than 10%, and the D values were 0.82, 0.89 and 0.90 respectively.

Yield

As shown in Figure 3, due to different varieties and environments, there are some differences in yield in each site, with an average of 10 150.28 ± 84.2 kg hm^{-2} in Longchuan, 10 552.25 ± 61.1 kg hm^{-2} in Ruili and 9718.5 ± 112.2 kg hm^{-2} in Mangshi. The yield value in Mangshi is obviously lower than that in other two sites, and the yield value in summer is obviously lower than that in winter. The simulated yield values of the three stations are 10664.1 ± 179 kg hm^{-2} in Longchuan, Ruili 10 303.6 ± 85.5 kg hm^{-2}, Mangshi 9845.8 ± 128.1 kg hm^{-2}. According to the comparison between the simulated values and the measured values (Figure 3), the simulated value and the measured value basically fall near the 1:1 line, and the yield prediction effect is good. The overall simulated value and the measured value have little difference. The total standard error of yield estimated in the three sites is 536.9 ± 78.9, 248.7 ± 87.7 and 365.4 ± 86.8 kg hm^{-2}. The comparison of different sites shows that the error of Mangshi is higher than the other two points. From the comparison of NRMSE, there is not much difference with the other two sites. The NRMSE of three sites yields is less than 5%, and the accuracy is high. The R^2 and D values of simulated and measured yields were 0.87-0.89 and 0.88-0.92, respectively. The NRMSE values of simulated and measured yields in Longchuan, Ruili and Mangshi were 2%, 3% and 5%, respectively, which were all lower than 10%. The validation results show that APSIM model can accurately simulate the change trend of maize yield in tropic of southwest China.

Figure 3. Comparison measured yield with simulation yield of different sowing dates and maize varieties in three sites.



a):Longchuan; b) Ruili; c) Mangshi. The dashed diagonal line is 1:1 line and insets are the values of RMSE.

The calibration and verification results of model parameters are highly dependent on the experiment data. This study is based on 10 field experiments with different sites and sowing dates, especially including winter sowing and summer sowing maize. The average temperature difference during the phenological phases is as low as 16.3 °C and as high as 26.8 °C, and the accumulated precipitation is as low as 58 mm and as high as 1267 mm. More obvious climatic and environmental differences help to improve the accuracy of model adjustment and verify the universality of the model. At present, most of the relevant domestic and overseas researches are based on field experiments in the same season and climate zone. For example, domestic scholars have conducted relevant research on summer sowing maize in North China Plain (Wang et al., 2007; Chen et al., 2009; Wang et al., 2015; Zhang et al., 2018; Zhao et al., 2018), spring sowing maize in Northeast China provinces (Liu et al., 2012; Lü et al., 2013; Huang et al., 2020) and summer sowing maize in Huang-Huai-Hai Plain (Wang et al., 2005; Li et al., 2013). Foreign scholars have made relevant studies on summer sowing maize in South Africa (Junior et al., 2021), spring sowing maize in Ethiopia (Feleke et al., 2021) and summer sowing maize in Nigeria (Beah et al., 2020). There are little differences in meteorological factors such as temperature and precipitation during the phenological phases in these study regions, so whether the results of parameter calibration can adapt in a wider region is limited in reliability.

The prediction accuracy of yield and phenological phases is high, and APSIM model is widely used to predict the growth period and yield of various crops in different areas. Among them, the prediction accuracy of phenological phases of winter wheat (Dai et al., 2015) in four sites in Chongqing is less than 3 d, the NRMSE of yield prediction is less than 20%, and the NRMSE of sugarcane yield prediction in Dehong, Yunnan is less than 10% (Mao et al., 2019). On maize, Zhang et al. (2018) and others verified APSIM model based on the data of summer maize in North China Plain from 1981 to 2015, and the NRMSE of yield prediction was below 7%. The prediction accuracy of yield and phenological phases in this study is better than that in previous studies, but there are still certain errors from the prediction accuracy among different sites in this study, and the error of emergence stage in Longchuan is as large as 10%, which is because the phenological phases are short, in fact, its RMSE is only 1.87 d, and the error fluctuates within the acceptable range.

Furthermore, APSIM model takes the accumulated temperature of each phenological phase as the basis for phenological prediction, and does not consider the difference of illumination and other factors, which is the defect of the model algorithm and leads to the systematic error of model prediction. Moreover, the uncertainty of variety parameters and input driving factors becomes an important reason for the inaccurate simulation results of the model. Due to the limitation of experimental data, there are still some shortcomings in the parameter calibration and validation of water and fertilizer and management modules in this paper, which need further study in the future.

CONCLUSIONS

The parameters of APSIM-Maize were calibrated and validated based on the field experiments under various environment with large climate differences. And the results showed that the prediction error of APSIM-Maize for growth period was 3.6 ± 0.7 d, and the prediction error of yield was 10078.47 ± 85.7 kg hm^{-2}. The error of phenological phases simulation value is generally less than 5.9 d, and the normalized root mean square error (NRMSE) of yield prediction is generally less than 4%. The prediction results of the model can also better reflect the difference of phenological phases and yield under different climatic environments, which shows that the model has both high accuracy and better sensitivity. Therefore, the APSIM-maize model has good adaptability in predicting the phenological phases and yield of maize sown in different seasons in the southwest tropical area by parameter calibration and validation.

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