DYNAMICS OF UNFOLDED LEAVES IN MAIZE (*ZEA MAYS* L.) AND THEIR MODEL ESTABLISHMENT BASED ON ACCUMULATED TEMPERATURE

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Abstract. The dynamic relationship between unfolding leaves and active accumulated temperature (AAT) of different maize (*Zea mays* L.) varieties was studied under different sowing dates, which would provide a theoretical basis for the realization of the informatization and digitalization of maize production on the Loess Plateau of China. Results showed that as the number of unfolded leaves increased, the number of days and the required active accumulated temperature to unfold one leaf showed a single peak trend. The unfolding of the 1st and the last leaves need the least time and AAT, while the 8th-15th leaves need the most. With the delay of sowing date, the peak value of the variation trend of the days and active accumulated temperature to unfold one leaf basically decreased gradually. Among different fitting models, the 3rd degree polynomial fitting model $y = a + bx + cx^2 + dx^3$ may have better biological significance and was thus adopted. As a result, the established models showed great variations in c and d parameters for different varieties, a and c for different sowing dates. The model was tested and showed that the simulated values were in good agreement with the actual values. The above results can provide valuable reference for the quantitative leaf unfolding and AAT requirement for maize and its adaptation to climate change.
Keywords: *number of unfolded leaves, simulation model, sowing date, climate change, Loess Plateau*

Introduction

Since the Industrial Revolution, global climate change caused by anthropogenic greenhouse gas emissions, e.g., CO_2, CH_4, N_2O, has led to a rise in global temperatures of approximately 1.25 °C (Voosen, 2021). Crop production can be affected by global warming, threatening the world-wide food production (Renard and Tilman, 2019; Gomez-Zavaglia et al., 2020). Climate change would have major negative impacts on crop production due to a decrease in crop growth duration and an increase in extreme events (Chen et al., 2018).

Identifying effects of warming on the maize (*Zea mays* L.) growth is particularly important as food security is highly dependent on maize production (Tigchelaar et al., 2018; Rotundo et al., 2019; Liu et al., 2020). Leaf growth and wilting could change the leaf area of maize and affect its photosynthesis and dry matter accumulation, thus affecting maize growth and yield (Testa et al., 2016; Meena et al., 2021; Yan et al., 2021). Active accumulated temperature (AAT) plays a decisive role in the growth of leaves (Zhou et al., 2020), being an important condition to improve the yield of maize.

As a major variable, accumulated temperature has been widely used in many mechanistic crop models to describe or simulate crop growth (Li et al., 2010, 2011; Liu et al., 2019; Wang et al., 2022), especially in leaf area dynamics. Recently, many studies have been conducted to determine the relationship between accumulated temperature and maize leaf area. For example, Zhang et al. (2007) studied and established a dynamic simulation model of relative leaf area index for spring maize, rice, and winter wheat. Li et al. (2011) reported the dynamic characteristics of leaf area coefficient under different sowing dates and planting densities with maize cultivars differing in maturity; the study also established a corresponding accumulated temperature model. The change of leaf area is determined by the unfolding and wilting of leaves, while leaf growth could be affected by the change of accumulated temperature, thus affecting crop yield (Zhu et al., 2021). To establish a mathematical model between unfolding leaves and AAT would be of great significance to study efficiently the growth and development of the maize, which can promote the quantification and digitalization of maize production.

Currently, many studies have been conducted on the relationship between the change of the maize leaf area index and accumulated temperature demand (Li et al., 2011; Wang et al., 2017), but few study have investigated the relationship between maize leaf unfolding and demand of accumulated temperature. In addition, climate change alters the phenology of maize, and the demand for accumulated temperature varies greatly among maize cultivars at different stages of maturity. The main purpose of this study is to improve the accuracy of leaf unfolding and accumulated temperature simulation, by increasing the observation frequency of leaf unfolding. Additionally, a dynamic model of the relationship between leaf unfolding and accumulated temperature would be established to analyze the effect of different sowing dates on the model, to determine the maize leaf growth dynamics in response to climate change, and to provide a theoretical basis for the digitization of maize production information.

Materials and methods

Site description

This study was conducted in the experimental station of Shanxi Agricultural University (112°59′E, 37°42′N) in Taigu, Jinzhong, Shanxi Province, China in 2012 and 2013. The field experiment located in the Jinzhong Basin, which has a temperate monsoon climate. The annual average temperature of this area is approximately 10 °C, the annual average precipitation is approximately 450 mm with precipitation mainly concentrated in June to August. The precipitation and air temperature in the growth and development stage of the maize were showed in *Figure 1* in both 2012 and 2013. The AAT was 3959.5 °C and 3801.9 °C, the total precipitation was 428 mm and 479.4 mm, and the total sunshine was 1760.8 h and 1378.7 h during the maize growing season in 2012 and 2013, respectively. The substance content in the 0-20 cm soil layer included 23.84 $g \cdot kg^{-1}$ of soil organic matter, 8.01 of pH, 0.775 $g \cdot kg^{-1}$ of total salt content, 0.750 $g \cdot kg^{-1}$ of total nitrogen, 1.227 $g \cdot kg^{-1}$ of total phosphorus, 24.74 $g \cdot kg^{-1}$ of total potassium, 42.41 $mg \cdot kg^{-1}$ of available nitrogen, 31.35 $mg \cdot kg^{-1}$ of available phosphorus, and 229.8 $mg \cdot kg^{-1}$ of available potassium.

Experimental design

In 2012, six maize cultivars were tested including the early maturity cultivars Xieyu Early 1 (ChongNongZuoPinShen 11) and Xinnong Early 3 (YuShenYu 2005008), medium maturity cultivars Xianyu 335 (GuoShenYu 2006026) and Zhengdan 958 (GuoShenYu 20000009), and mid-late maturity cultivars Dafeng 26 (JinShenYu 2009003) and Luyu 36 (JinShenYu 2012009). Five sowing dates (April 26, May 6, May

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16, May 26, and June 5) were set for 30 treatments. The maize cultivars tested in 2013 were the same as those in 2012, but the sowing dates were adjusted. In general, the conventional sowing date ranged from late-April to early-May in the region of the study. Six sowing dates (April 1, April 11, April 21, May 1, May 11, and May 21) were used in 2013 for a total 36 treatments. Thereto, the normal and late sowing dates were set in 2012, excluding the early sowing date. In order to assess the effect of sowing date on unfolding leaves, the sowing dates were optimized and added the early sowing dates, i.e., April 1 and April 11 in 2013. Each plot covered an area of 36 m^2 (length 10 m × width 3.6 m) and included eight rows with the planting technique of alternating wide to narrow rows (50 cm: 40 cm). The row spacing was 29.6 cm and the planting density was 75, 000 plants·ha^{-1}.

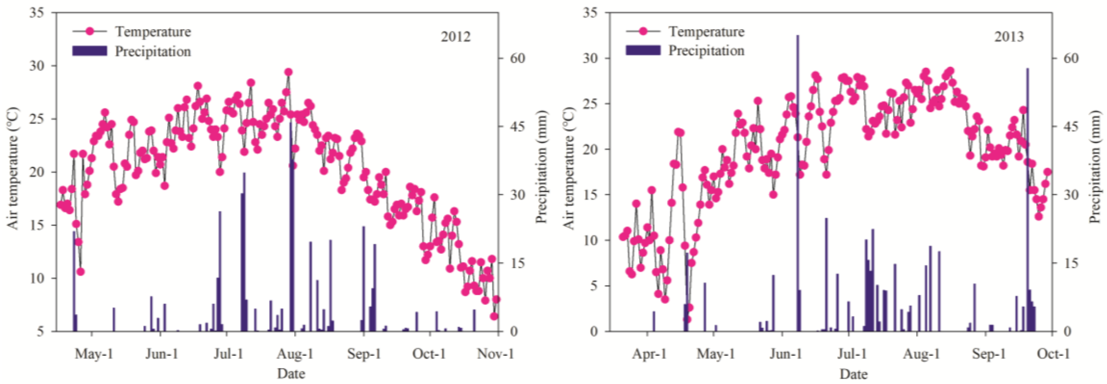

Figure 1. *The distribution of the precipitation and air temperature in the growth and development stage of the maize in both 2012 and 2013*

In 2012, the experimental field was well irrigated on April 20. Around 600 kg·ha^{-1} of phosphorus-potassium nitrate fertilizer (N-P_2O_5-K_2O = 22-9-9), provided by Shanxi Tianji Coal Chemical Group Co., Ltd., was used as basal fertilizers for all plots on the afternoon of April 22. The field was rotovated to a depth of ~8-10 cm on the morning of April 23. The insecticide Dursban was used to prevent underground insects on April 25. After the herbicide of butachlor (4%) -propisochlor (20%) -atrazine (18%) was applied to prevent the weeds on April 26, the film was mulched over the ground all plots. Then, the maize was sown at different sowing dates according to the experiment design. Above farming practices were inconsistent because of the precipitation during this period. Moreover, the film was removed after the maize emerged for each plot. Around 375 kg·ha^{-1} of urea (46% N) as topdressing was used for each plot, which was carried out for the first three sowing dates (i.e., April 26, May 6, May 16) on June 29, and the last two sowing dates (i.e., May 26, and June 5) on July 9. The maize in all the plots had been harvested by October 31.

In addition, in order to ensure soil moisture content for sowing in 2013, a series of farming operations were conducted on November 9, 2012. First of all, the soil was plowed to a depth of ~25-30 cm. Then, around 600 kg·ha^{-1} of compound fertilizer (N-P_2O_5-K_2O = 30-10-0), provided by Yunan Yuntianhua Co., Ltd., was used as basal fertilizers for all plots. Whereafter, the field was rotovated to a depth of ~8-10 cm and leveled. The insecticide Dursban was applied, then the film was mulched over the ground all the plots. In 2013, after the maize was sown at different sowing dates

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according to the experiment design, the herbicide was applied. Likewise, we removed the film for each plot after the maize emerged. And around 375 $kg \cdot ha^{-1}$ of urea was used as topdressing for each plot, which was carried out for the first five sowing dates (i.e., April 1, April 11, April 21, May 1, May 11) on June 12, and the last one sowing dates (i.e., May 21) on June 20. The maize in all the plots had been harvested by September 28, 2013.

Determination items and methods

After germination, 10 plants with identical growth were selected and marked for each treatment, and the number of visible leaves and unfolded leaves were recorded daily until all the leaves unfolded. Visible leaf refers to a leaf with the heart leaf exposed 1–2 cm before the jointing stage and exposed 5 cm after the jointing stage. A leaf was considered unfolded leaf when the leaf pulvinus extended out of the leaf sheath of the adjacent lower leaves and the blade completely unfolded. The days required for maize leaf unfolding referred to the time from the heart leaf being visible to the lower leaf completely growing out of the ligule and the leaf sheath being exposed. The accumulated temperature was measured as the accumulation of daily mean temperature (≥10 °C) of maize leaves from the visible to unfolded leaf periods.

The temperature record and accumulated temperature calculation were conducted by an automatic weather station in the test field, and the daily basic meteorological data were automatically measured hourly. A Watch Dog Data Logger (United States) was hung in a louver at the weather station approximately 1.5 m above ground to record the temperature at the test field hourly. The daily mean temperature (T_{mean}) was calculated by using the temperature recorded every two hours from 0 o'clock every day (*Eq. 1*). The AAT (T_{accum}) was the accumulation of daily mean temperature (≥10 °C) (*Eq.* 2) (McMaster and Wilhelm, 1997; Liu et al., 2019).

$$T_{mean} = \sum_{i=1}^{12} T_i / 12 \quad \text{(Eq.1)}$$

where T_{mean} is the daily mean temperature (°C), and T_i is the temperature recorded every 2 h from 0 o'clock (°C).

$$T_{accum} = \sum_{j=1}^{n} T_{mean,\, j(\geq 10^{o}\mathrm{C})} \quad \text{(Eq.2)}$$

where T_{accum} is active accumulated temperature (°C), j is the daily mean temperature ≥ 10 °C.

Data analysis

Using the data measured in 2012 and the method of normalization, the AAT and total number of leaves from the emergence stage to leaf unfolding were set to 1 in all treatments, so that the relative AAT and relative unfolded leaf numbers could range from 0 to 1. In this study, Curve Expert 1.4 was used to dynamically simulate the relative number of unfolded leaves and relative AAT of all cultivars and sowing date, and different maize maturities and different sowing dates. The model was tested using

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the unfolded leaf number of maize measured in 2013. Normalized Root Mean Square Error (*NRMSE*) was used to evaluate the relative difference between measured and simulated values, and Index of Agreement (I) was used to test the consistency between measured and simulated values. *NRMSE* and *I* were calculated using *Equations 3–6*, respectively (Bai et al., 2011).

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - R_i)^2}{n}} \times \frac{100}{\bar{R}} \qquad \text{(Eq. 3)}$$

$$I = 1 - \left[\frac{\sum_{i=1}^{n}\left(S_i - R_i\right)^2}{\sum_{i=1}^{n}\left(\left|S_i^{'}\right| + \left|R_i^{'}\right|\right)^2} \right] \qquad \text{(Eq.4)}$$

$$S_i^{'} = S_i - \bar{R} \qquad \text{(Eq.5)}$$

$$R_i^{'} = R_i - \bar{R} \qquad \text{(Eq.6)}$$

where S_i is the simulated value, R_i is the measured value, $\bar{R}$ is the average measured value, and *n* is the sample number of the simulated value. When *NRMSE* < 10%, the fit was considered excellent; when 10% ≤ *NRMSE* ≤ 20%, the fit was good; when 20% ≤ *NRMSE* ≤ 30% the fit fell in the middle; and when *NRMSE* > 30%, the fit was considered bad. When the value of ‘*I*’ is closer to 1, the consistency between the simulated and measured number is better, otherwise the this is the contrary. All figures in the study were drawn by Sigmaplot 12.0.

Results

The number of days and AAT needed for leaf unfolding

As shown in *Figure 2*, under different sowing dates of six maize cultivars, the number of days needed for leaf unfolding fit a unimodal curve that first increased and then decreased with the increase of leaf position. The number of days needed for each leaf unfolding ranged from 1 day to 18 days, of which the first, second, and last leaves needed less than a day to unfold, while the eighth to 14th leaves required additional days. With the postponement of the sowing date, the peak value of the days needed for leaf unfolding of different maize cultivars showed a decreasing trend, namely, April 26 > May 6 > May 16 > May 26 > June 5.

Similar to the above results, the AAT of each leaf unfolding increased first and then decreased with the increase of leaf position (*Fig. 3*). The AAT required for one leaf to unfold ranged from 16.6 °C to 388.1 °C, of which the first, second, and last leaves needed less AAT, while the ninth to 15th leaves needed additional time and accumulated temperature. Similar to the results of days required for leaf unfolding, the peak value of accumulated temperature for leaf unfolding of different maize cultivars gradually decreased with the delay of sowing date, which was April 26 > May 6 > May 16 > May 26 > June 5.

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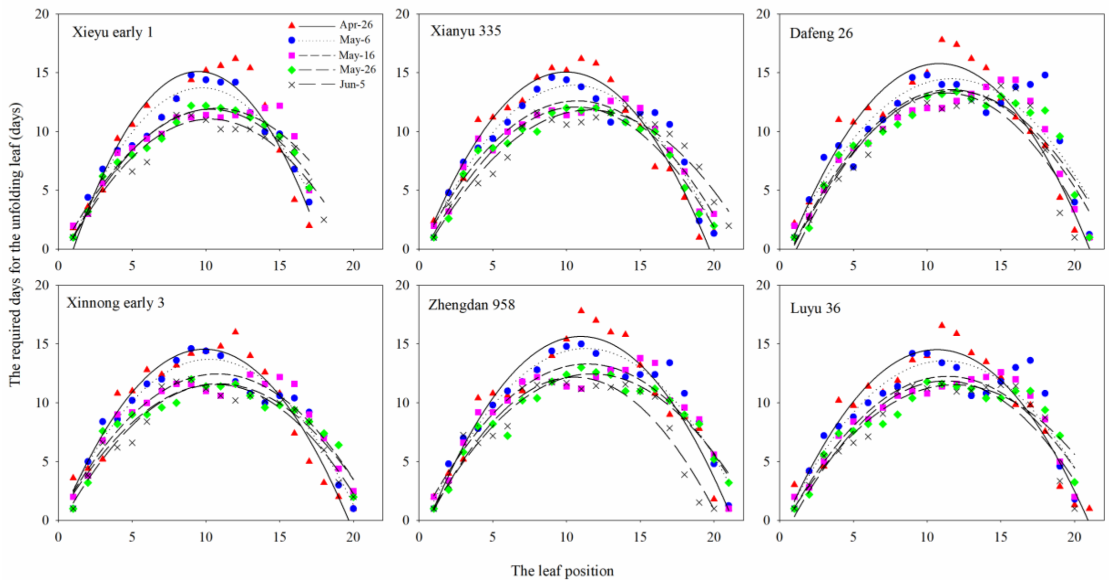

Figure 2. *The number of days to unfold each leaf for different sowing dates and cultivars in 2012*

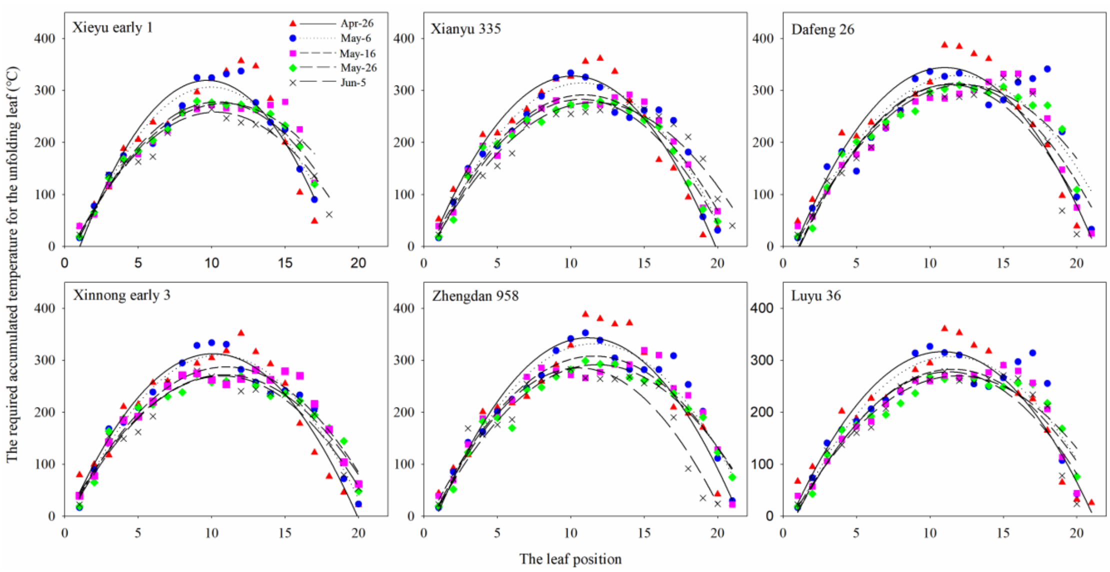

Figure 3. *The AAT needed to unfold each leaf for different sowing dates and cultivars in 2012*

Establishment of a model of relative number of unfolded leaves

The AAT and the number of unfolded leaves required for leaf unfolding of maize cultivars with different maturities in five sowing dates in 2012 were normalized. Each cultivar and sowing date was also normalized. Curve Expert 1.4 was used to simulate the relative number of unfolded leaves and relative AAT. The six models with the best simulations were selected including cubic equation, rational function, Hoerl model, quadratic equation, Shifted power fitting, and sinusoidal function. The determinant coefficients of these models were over 0.9900, and their standard deviations were less than 0.03 (*Table 1*).

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Table 1. *Models employed to fit the observed relative number of unfolded leaves against the relative accumulated temperature and the parameters obtained for each model*

Simulated model	**Parameters of each model**				**Standard deviation**	**Determination coefficient**
	a	***b***	***c***	***d***		
$y = a + bx + cx^2 + dx^3$	0.0368	0.9203	-0.6774	0.6873	0.0236	0.9934^{**}
$y = (a + bx)/(1 + cx + dx^2)$	0.0392	0.9109	0.7472	0.7882	0.0235	0.9933^{**}
$y = a*(b\text{^}x)*(x\text{^}c)$	0.3234	3.0264	0.4428	-	0.0242	0.9930^{**}
$y = a + bx + cx^2$	0.0727	0.4739	0.4181	-	0.0275	0.9909^{**}
$y = a(x-b)\text{^}c$	0.5389	-0.3658	1.8755	-	0.0279	0.9907^{**}
$y = a + b*cos(cx + d)$	1.7490	1.7589	0.7923	3.4548	0.0286	0.9902^{**}

In the model, *x* and *y* represent the relative accumulated temperature and relative number of unfolded leaves, respectively. **Significance is at a probability level of 0.01

The results of the six simulation models all performed well (*Table 1*), thus the clearer physical meaning of simple polynomials, quadratic, and cubic polynomial equations were chosen. Based on this, a fitting diagnosis (*Fig. 4*) was conducted using the relative number of unfolded leaves and the standardized residuals obtained from the relative number of unfolded leaves. Two equations showed that the standardized residual distribution of the cubic polynomial equation was more uniform than that of the quadratic polynomial equation. Therefore, the cubic polynomial equation was used in this study for the simulation analysis. In the cubic polynomial equation, when $x = 0$, $y = a$, which means the value of '*a*' was the relative number of unfolded maize leaves at the emergence stage; when $x = 1$, $y = a + b + c + d$, of which the $(a + b + c + d)$ was the relative number of maize leaves completely unfolded. By using the cubic polynomial equation, any relative number of unfolded leaves corresponding to relative AAT can be simulated, and the dynamic change of unfolded leaf number can be observed over time.

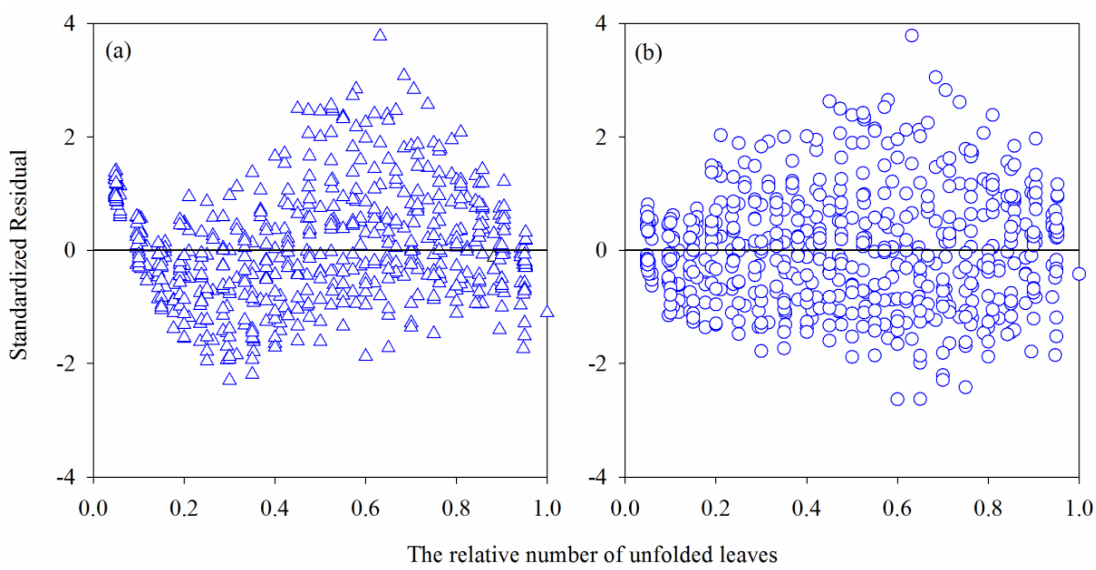

Figure 4. *The standardized residual distribution between the relative number of unfolded leaves with quadratic (a) and cubic (b) regression equations, respectively*

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Analysis of key parameters for the dynamic model of the relative number of unfolded maize leaves of different cultivars and sowing dates

Based on the above analysis, the parameters of the dynamic model of the relative number of unfolded leaves of maize cultivars with different maturities and sowing dates were further studied. The results showed that the simulation effects of relative AAT and the relative number of unfolded leaves in all treatments in 2012 reached a very significant level, and the coefficient of variation (CV) was higher than 0.9900. In *Table 2*, the CVs of model parameters '*c*' and '*d*' of maize with different maturities were large, -28.66% and 21.80%, respectively, while those of '*a*' and '*b*' were relatively small, which indicated that '*c*' and '*d*' were the main parameters to explain the variation of simulated equation of relative unfolded leaf number of maize with different maturities. The CVs of various parameters of maize cultivars with the same maturity were different. The variation of parameters '*a*', '*b*', and '*c*' in the early maturity maize cultivars was relatively high, while that of '*a*', '*c*', and '*d*' in the medium maturity cultivars was also higher. The variation of '*c*' and '*d*' in the mid-late maturity cultivars was also high. Comparing the model parameters of all maize cultivars, the variations of parameters '*c*' and '*d*' were larger, -24.72% and 18.52%, respectively, while those of parameters '*a*' and '*b*' were smaller. This indicates that '*c*' and '*d*' were the dominant parameters affecting the simulation equation of the relative unfolded leaf number of different maize cultivars, but the dominant parameters of the simulation of different maize cultivars at the same level of maturity were different.

Table 2. *Models employed to fit the observed relative number of unfolded leaves against the relative accumulated temperature and the parameters obtained for each model of different maize cultivars*

Cultivar	Parameters of each model				Standard deviation	Determination coefficient
	a	***b***	***c***	***d***		
Early maturity	0.0349	0.9590	-0.8698	0.8640	0.0237	0.9934**
Xieyu Early 1	0.0316	1.0727	-0.9835	0.8695	0.0169	0.9968**
Xinnong Early 3	0.0271	0.9167	-0.8610	0.9047	0.0180	0.9964**
CV for early maturity*	10.84	11.09	-9.39	2.81		
Medium maturity	0.0369	0.8491	-0.5061	0.6067	0.0214	0.9946**
Zhengdan 958	0.0361	0.8743	-0.5965	0.6650	0.0232	0.9937**
Xianyu 335	0.0321	0.8688	-0.5103	0.6061	0.0179	0.9964**
CV for medium maturity*	8.29	0.45	-11.01	6.55		
Mid-late maturity	0.0383	0.9485	-0.6002	0.6002	0.0184	0.9960**
Luyu 36	0.0328	0.9952	-0.6297	0.5944	0.0167	0.9968**
Dafeng 26	0.0340	0.9757	-0.7145	0.6882	0.0177	0.9964**
CV for mid-late maturity*	2.54	1.40	-8.92	10.34		
CV among maturities#	4.66	6.60	-28.66	21.80		
CV among cultivars※	9.31	8.31	-24.72	18.52		

* is the coefficient of variation (CV) among different cultivars under a certain maturity, # is the CV among different maturities, ※ is the CV among six maize cultivars. ** Significance is at a probability level of 0.01

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In addition, the analysis of the dynamic regression model parameters of the relative unfolded leaf number of maize under different sowing dates (*Table 3*) showed that the CVs of parameters '*a*', '*c*', and '*d*' were very large; the model parameters simulated at the sowing date of April 26 were quite different from the others. If the data from April 26 were not taken into account, the variation of parameters '*a*' and '*c*' was larger, while that of '*b*' and '*d*' was smaller. Therefore, '*a*' and '*c*' were the main parameters explaining the variation of the relative number of unfolded maize leaves in the models under different sowing dates. Theoretically, the value of parameter '*a*' in the model should be 0, and its fitted value in this study was close to 0. The '*b*' value should change at approximately 1, which is determined by the normalization. Thus, the range of the dependent variable (*y*) and independent variable (*x*) varied from 0 to 1. In summary, except for the sowing date of April 26, the parameters '*a*' and '*b*' of the models under different cultivars and other sowing dates were relatively stable, while the relative changes of '*c*' and '*d*' were largely variable.

Table 3. *Models employed to fit the observed relative number of unfolded leaves against the relative accumulated temperature and the parameters obtained for each model of different sowing dates*

Sowing date	**Parameters of each model**				**Standard deviation**	**Determination coefficient**
	a	***b***	***c***	***d***		
April 26th	0.0099	1.0680	-1.0949	1.0017	0.0195	0.9956**
May 6th	0.0377	0.9215	-0.6805	0.7047	0.0216	0.9946**
May 16th	0.0321	0.9367	-0.5862	0.6096	0.0185	0.9961**
May 26th	0.0433	0.8513	-0.5301	0.6248	0.0228	0.9940**
June 5th	0.0378	0.9907	-0.7270	0.6901	0.0202	0.9953**
Coefficient of variation	40.61#	8.49	-30.59	21.94		
	12.12※	6.21	-14.13	7.17		

# indicates the coefficient of variation (CV) among all sowing dates, ※ indicates the CV except for April 26th. ** Significance is at a probability level of 0.01

Inspection and application of dynamic models of the relative number of unfolded leaves

Generally, the AAT required by a certain maize cultivar is constant (Li et al., 2011), therefore, the relative AAT after normalization is also considered stable. Combined with the daily investigation of maize leaf unfolding, the observed accumulated temperature was substituted into the simulation equation to get the corresponding relative unfolded leaf number, and then the real-time unfolded leaf number could be calculated by multiplying the total leaf number of this cultivar by the relative unfolded leaf number at the growing period. The model established by different cultivars and sowing dates was tested with the data in 2013, and the 1:1 test chart of measured and simulated values of unfolded leaf number was obtained (*Figs. 5* and *6*). When validating the measured and simulated number of different cultivars, the equations established by different cultivars and those established by all cultivars together were also tested in this study. The results showed that NRMSE was less than 15%, and I and I1 were close to 1, indicating that the measured number of unfolded leaves of six maize cultivars was in good agreement with the simulated number of the two equations, but the simulated number was slightly

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higher than the measured number. Because of the difference of sowing dates between years, the number of unfolded leaves under different sowing dates was simulated based on the equation established by all sowing dates in this study, and this fit the measured numbers. The results indicated that NRMSE was less than 15%, and I and I1 were close to 1, which showed that the consistency between simulated and measured numbers was good. The fitted value was slightly higher than the measured value when the number of unfolded leaves was less than five, while the simulated value was lower than the measured value when the number of unfolded leaves was more than five. In summary, the model parameters established by the relative unfolded leaves of different cultivars were slightly different from those established by all cultivars together, but the simulation level of these two models was very high, which indicated that the model has wide application.

Discussion

The dynamic of unfolded maize leaves affects the leaf area index, photosynthesis, and yield of crop plants (Wang et al., 2018). Temperature is one of the most important environmental and ecological factors affecting the dynamics of unfolded maize leaves and yield formation (Yan et al., 2009), which determines the yield of maize and whether a maize variety can be planted in a certain area (Daiet al., 2008). The AAT is an important reflection of the effect of temperature change on crop growth (Pan et al., 2011).

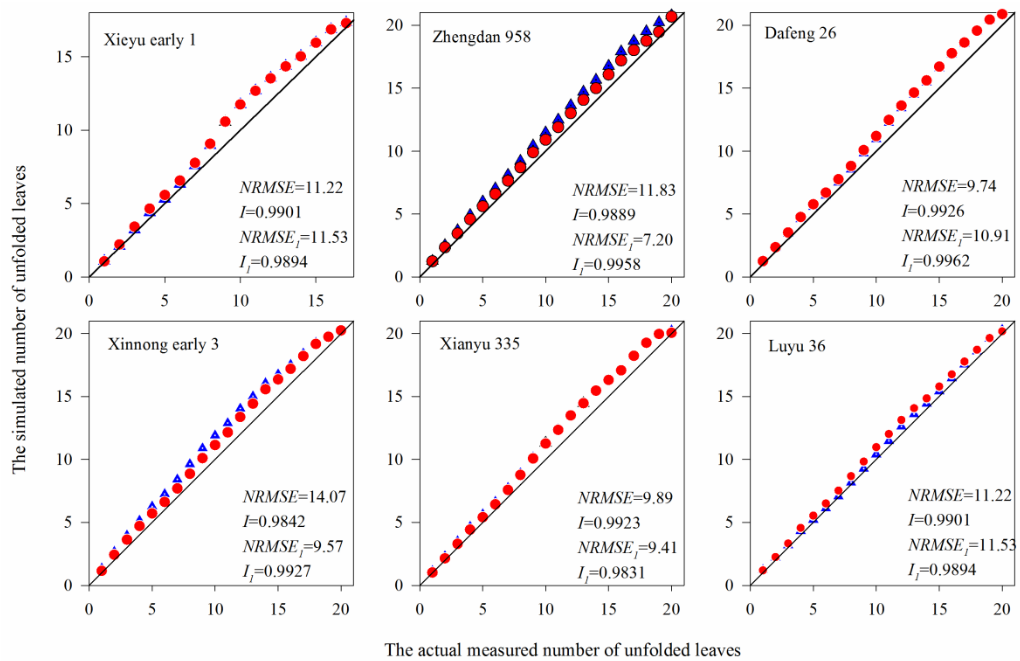

Figure 5. *The test chart of the simulated number of unfolded leaves and the actual measured number of unfolded leaves in maize for different cultivars. NRMSE and I indicate the normalized root mean square error and index of agreement, respectively. The "1" in lower right-hand corner of NRMSE and I is the value based on the model of each maize cultivar. The blue triangle indicates the simulated value through the mathematical model which was establish by all maize cultivars, while the red circle indicates the simulated value through the mathematical model which was establish by each maize cultivar*

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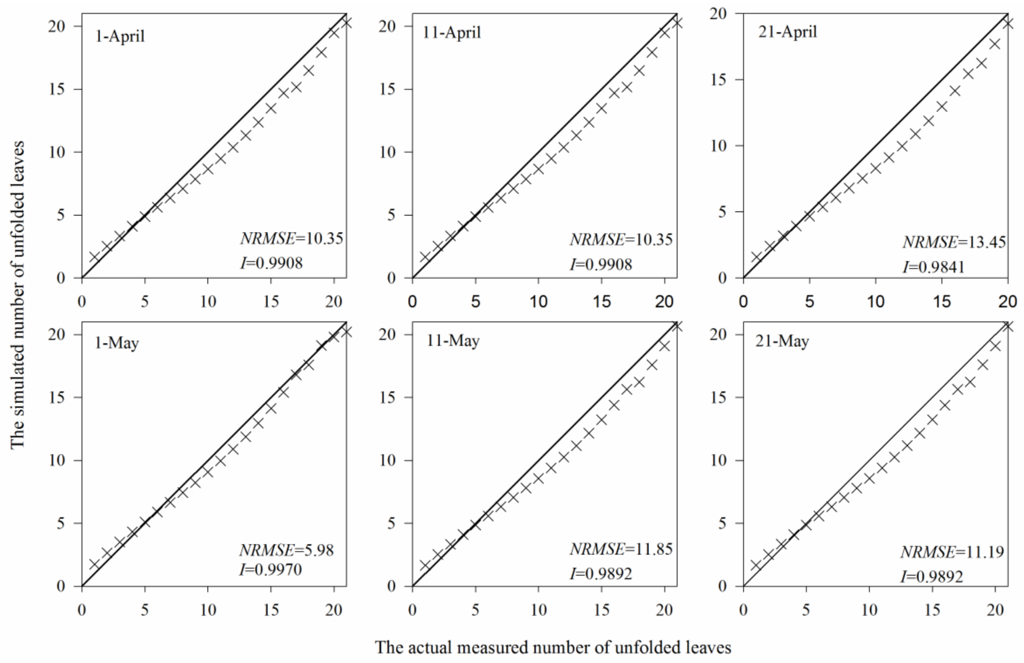

Figure 6. *The test chart of the simulated number of unfolded leaves and the actual measured number of unfolded leaves in maize under different sowing dates. NRMSE and I indicate the normalized root mean square error and index of agreement, respectively. The "1" in lower right-hand corner of NRMSE and I is the value based on the model of each maize cultivar*

The results of this study showed that the number of days and accumulated temperature, needed for leaf unfolding of six maize varieties, presented a unimodal trend with the increase of leaf position. The first, second, and last leaves needed fewer days and less AAT to unfold, while the eighth to fifteenth leaves needed additional days and AAT. This result might be mainly due to the following reasons. First of all, there were usually larger leaves from the eighth to fifteenth leaves, which would require the absorption of more nutrients to accumulate dry matter. Then, the larger the unfolded leaves were, the more days they needed to absorb nutrients for dry matter accumulation. Furthermore, the effects of the environmental factors could be stronger by those larger leaves. Lower air temperature could inhibit the development of the first leaves compared with larger leaves.

This study showed that with the postponement of the sowing date, the peak value of the days and AAT required for maize leaf unfolding decreased. With the delay of the sowing date, the growth process of maize was accelerated and the growth period was gradually shortened (Xie et al., 2005), reducing the number of days needed for most leaves to unfold. Although the accumulated daily temperature was greater during leaf unfolding, the accumulated active temperature decreased in general.

The study of crop growth models is of great significance to the development of modern agriculture (Boote et al., 2018). In this study, maize leaves were observed daily, with an average of 12 observations per day and 12 measurements for the standard value of daily average temperature per day. The AAT and total number of leaves required for maize varieties with different stages of maturity from emergence to leaf unfolding at different sowing dates were normalized. The relative number of unfolded leaves and relative AAT after normalization were simulated, by establishing the dynamic model of

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the relative number of unfolded leaves: $y = a + bx + cx^2 + dx^3$. The parameters of the model have great biological significance, where the value of 'a' is the relative unfolded leaf number of maize at the emergence stage, and the value of $(a + b + c + d)$ is the relative unfolded leaf number at the heading stage.

In this study, comparisons of models established by six maize varieties showed that the variation of model parameters between varieties was mainly '*c*' and '*d*' and that of model parameters at different stages of maturity presented similar results. However, the model parameters among varieties at three maturities (early maturity, middle maturity, and mid-late maturity) was different, in which the CV of '*a*' and '*c*' was the largest and '*b*' was the smallest.

By comparing the values, the simulated values of the model established by all varieties together and those made by each variety separately were slightly higher than the measured values, which may be resulted from the difference of maize growth and development between years. The results of *NRMSE* and *I* tests demonstrated that these two models were in good agreement, indicating that the models based on all varieties can be applied to the simulation of unfolded leaf number of different varieties. When the required AAT and the total number of leaves are known, the relative number of unfolded leaves corresponding to any relative AAT can be accurately obtained. This provides a timely method to control the dynamic changes of the number of unfolded leaves and provides the corresponding basis for the digitization of maize production information.

At present, global climate change has become the focus of scientists from all fields. Considering the overall temperature increase in the future, late sowing can be regarded as an environmental condition of the future, so it can be used to evaluate the adaptation of maize leaf growth to climate change to a certain extent. The results of this study showed that the rising temperature in the future could reduce the number of days and accumulated temperature required for most maize leaves to unfold. In addition, besides the leaf unfolding, leaf withering also has a great impact on the leaf area index. Therefore, it is necessary to further analyze the combined dynamics of the processes of leaf unfolding and withering to analyze and predict the change of the leaf area index.

In current study, the mathematical relationships between unfolding leaves and AAT were assessed, which would be more efficient and concise to study the growth and development of the maize. However, leaf area index, depended on the unfolding and wilting of leaves, is a very important indicator in the general research. Then, there would be much more meaningful to establish the mathematical relationships between leaf area index and AAT. In addition, in order to testify the applicability and validity of the current model widely, more field trials would be carried out in different ecological zones in future study. Furthermore, the dynamic relationship between unfolding leaves and AAT under other cultivation practices would be considered in the future research.

Conclusions

Based on different cultivars and sowing dates, the number of days required for each leaf unfolding and the needed accumulated temperature were analyzed. A dynamic model of the relative number of unfolded leaves was established. The main conclusions are as follows:

(1) With the increase in the number of unfolded leaves, the number of days needed for leaf unfolding and accumulated temperature of different maize cultivars showed a

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unimodal trend. The eighth to the fifteenth leaves needed more days and a higher accumulated temperature compared to that needed by the first, second, and last leaves. With the postponement of the sowing date, the peak value of the variation of days needed for leaf unfolding and AAT showed a decreasing trend.

(2) The cubic polynomial equation $y = a + bx + cx^2 + dx^3$ showed the best simulation effect between the relative number of unfolded leaves and relative AAT of maize. The parameters of this model have great biological significance, which can accurately predict the dynamic changes of the number of unfolded leaves.

(3) The result could provide a theoretical support that through the optimization of sowing date promoting effectively the adaptation of maize production to climate change in the future.

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