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Mechanistic Model of Spike Differentiation and Phenological Development of Maize (*Zea mays*) Based on the Physiological Development Time

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Abstract

A simulation model for maize spike differentiation and phenophase was established by analysis of temperatures and illumination treatments effects on maize growth and development process based on physiological development time constancy. Specific Bata function was applied in the model to calculate the daily thermal effect, and Gaussian function for photoperiodic effects. Temperature sensitivity, photoperiod sensitivity, intrinsic earliness and filling fractions which are genetic coefficients used to express genetic differences of maize development process. The model was tested at different growth stages and nitrogen factor was corrected by the actual nitrogen content, the critical nitrogen content and the lowest nitrogen content of plant. Results demonstrated that the absolute simulation error on growth stages (including emergence, jointing, silking, filling and maturity) and tassel and ear differentiation stages (including growing tip lengthening, spikelet differentiation, floret differentiation stage and sexual organ development) in different maize (*Zea mays* L.) cultivars was between 0-5 d, and the root mean square error was found less than 3.5 d. The proposed model demonstrated that the mechanism is rational and practical.

Keywords: Maize; Spike differentiation; Phenophase; Simulation

Introduction

Agricultural information technology is a new cross-discipline that was established with the rapid development of information science and accumulation of advanced agricultural knowledge, which is going to make a profound and extensive influence on the agricultural science and production. Therefore, as the core content and base of agricultural information, crop simulation technology provides a bridge and inter-connects intelligent, precise and digitalization of global agricultural production (Chao and Luo, 2000). Growth period model is important content of crop simulation. It could forecast crop yield and quality, arrange suitable farming system, take agronomy practices in a timely fashion, explain and quantize the influence of environmental factors on crop growth, exact predicate flower bud differentiation and phenophase, develop studies on physiological and ecological aspects, production management and decision support system.

Crop growth and development is affected by temperature, light intensity, nitrogen, moisture (Travis *et al*., 1988; Mirschel and Kretschmer, 1990; Mirschel *et al*., 1990). Therefore, these factors are used as factors affecting crop growth to construct growth period model, and a lot of this model were constructed by previous studies (Bruhn *et al*., 1980; Hodges, 1991; McMaster *et al*., 1992; Goudriaan and Van Laar, 1994; Mirschel *et al*., 2005; Timsina and Humphreys, 2006; Sharma and D'Antuono, 2011). In general, the current model construction idea was derived from the accumulated temperature and physiological development time method. Accumulated temperature method is usually used to forecast crop growth period. It was hypothesized that crop growth rate is linear positive correlation with average temperature (De Wit *et al*., 1970; Penning de Vries *et al*., 1989). It is easy to calculate; however, it has certain limitations that it doesn't take into account the duration of day, only temperature, and hypothesizes that crop growth rate is linear positive correlation with average temperature. Physiological development time method was developed based on the theory of physiological development time constant, widely used for growth period simulation of field crops by synthesized temperature and illumination effects. Physiological development time means the time required to complete a crop development stage under the optimal situation of temperature and illumination. Physiological development time constant means the physiological development time necessary to complete a development stage in a particular genotype varieties remains essentially constant (Chao and Luo, 2000).

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Parameters were determined by thermal and illumination effects in the growth model which is based on physiological development time. Yan (2000) constructed a mechanistic model of wheat, imported temperature sensitivity, vernalization time, photoperiod sensitivity and basic early maturity to reflect their hereditary characters. Meng *et al.* (2003) constructed a process based model for simulating phasic development and phenology in rice, imported specific genetic parameters sensitive to photoperiod, temperature, optimum temperature, basic early maturity and filling fraction in five plant varieties (Meng *et al.*, 2003). In addition, studies of model on apical development and phonological stages in barley (Xu *et al.*, 2006; Zou *et al.*, 2009), simulation model for cotton development stages (Zhang *et al.*, 2003), model for simulating phonological development in rapeseed (Tang *et al.*, 2008), mechanism model for flower bud differentiation and phenophase of soybean (Chen *et al.*, 2012a), are all based on the physiological development time constant, and imported parameters of photoperiod and temperature sensitivity, basic early maturity and filling fraction.

There are some studies (Allan Jones and Dyke, 1986; Zheng and Gao, 2000) on simulation model for maize (*Zea mays* L.) which are relatively simple and could not reflect the effects by many environmental factors such as nutrition and water. The dynamic simulation model of maize growth in northeast China (Chen *et al.*, 2012b) focused only on thermal effect and not on illumination effect. The simulation model of maize phenology by Zheng and Gao (2000) focused on thermal and illumination effects, but did not consider the effect of nitrogen on plant. The study on simulating maize spike differentiation is currently lacking. The objective of this study was to establish time coordinate for maize organ morphogenesis model and the yied and quality formation model, which could quantify the dynamic prediction and management of maize spike differentiation and growth period, and laid the foundation for the decision support system of maize produce.

Materials and Methods

Experimental Materials

In this study, four local and high yielding maize varieties (Zhengdan958, Xianyu335, Jinshan27 and Weike702) were selected. The growth period of Zhengdan958, Jinshan27 and Weike702 are longer than Xianyu335.

Experimental Design

Experimental field: There were 4 experiments in this study, experiment 1 and 2 were conducted at experimental farm of the College of Agriculture, Inner Mongolia University for the nationalities (A) in 2011 and 2012. The experiment 3 was conducted at the experimental farm of Chifeng Academy of Agricultural and Animal Husbandry Sciences (B) in 2012 and the last and final experiment 4 was conducted at experimental farm of the Inner Mongolia Agricultural University (C) in 2012. Details of these experimental fields are presented in Table 1.

Field experiment design: Experiment 1: Four maize varieties (Zhengdan958, Xianyu335, Jinshan27 and Weike702) were used in a split block design. Nitrogen application levels were 0 kg·ha^{-1}, 210 kg·ha^{-1}, 300 kg·ha^{-1} and 390 kg·ha^{-1} (pure Nitrogen) and each fertilized at seeding, jointing and flare opening stage (13th leaf un-fold) with ration of 1:3:6. Planting density was 7.5×10^4·ha^{-1}. Base fertilizer included were phosphate (P_2O_5) 190 kg·ha^{-1} and potash fertilizer (K_2O) 80 kg·ha^{-1}. Plot area for seeding was 60 m^2 with 3 replications. Cultivation and management measures followed according to standard field production after sowing on 28th April.

Experiment 2: Four maize varieties were arranged random with 3 replications. Fertilization level, planting density and cultivation and management measures were same as described for experiment 1, 300 kg·ha^{-1} (pure Nitrogen) nitrogen application level which was fertilized at seeding, jointing and flare opening stage（13th leaf unfold) with ration of 1:3:6, except for the base fertilizer included were phosphate (P_2O_5) 190 kg·ha^{-1} and potash fertilizer (K_2O) 80 kg·ha^{-1}, with two sowing times (27th April and 11th May respectively).

Experiment 3 and 4: Same design as described for experiment 2, except for the fact that they were sown on 4th May and 5th May, respectively.

Observations Recorded

Growth stages (including seeding, elongation, silking, grain filling and maturity) spike differentiation (including growing tip lengthening, spikelet differentiation, floret differentiation stage and sexual organ development) of experiments 1 and 2 were observed and recorded. The growth stage of experiment 3 and 4 were also recorded. Young ear development stages were observed under electronic anatomical lens. Single standard was used to distinguish different growth stages and young ear development stages (Zhang *et al.*, 2003). Daily maximum, minimum and average temperature and duration of day were provided by the local meteorological station.

Data Processing and Using

Meteorological data was calculated by Microsoft®Excel™. The data for the experiments 1 and 2 sown on May11th was used to construct model and test the parameters. The data for experiment 2 sown on April 27th, and of experiments 3 and 4 was used to test the model.

Equations to Calculate

Daily thermal(RTE) and photoperiodic (RPE)effects (Xu *et al.*, 2006):

$$RTE(I)=\begin{cases}0 & T_{emp}(I)<T_b\\ \dfrac{T_{emp}(I)-T_b}{T_l-T_b} & T_b\le T_{emp}(I)<T_l\\ 1 & T_l\le T_{emp}(I)<T_u\\ \dfrac{T_m-T_{emp}(I)}{T_m-T_u} & T_u\le T_{emp}(I)<T_m\\ 0 & T_{emp}(I)\ge T_m\end{cases} \quad (1)$$

$$RPE(I)=\begin{cases}0 & DL<DL_c\\ \dfrac{DL-DL_c}{DL_o-DL_c} & DL_c\le DL\le DL_o\\ 1 & DL_o<DL\end{cases} \quad (2).$$

Where, Tb = cardinal temperature, Tl = optimum lower temperature, Tu = optimum upper temperature, Tm = maximum temperature, DLc = critical duration of day, DLo = optimum duration of day, DL = actual duration of day.

Temperature and growing degree days (GDD) of time intervals of day (Chao and Luo, 2000):

$$T_{emp}(i)=T_{min}+T_{fac}(i)(T_{max}-T_{min}) \quad (3)$$

$$T_{fac}(i)=0.931+0.114i-0.0703i^2+0.0053i^3, i=1,2,3\ldots8 \quad (4)$$

$$DTT=1/8\sum_{i=1}^{8}(T_{emp}(i)-T_b) \quad (5)$$

$$GDD=\sum DTT \quad (6).$$

Where, $T_{emp}(i)$ = average temperature each of these 8 time intervals in one day, T_{min} = minimum temperature, T_{max} = maximum temperature, $T_{fac}(I)$ = temperature variation factor, T_b = cardinal temperature, DTT = daily thermal time, GDD = sum total thermal time daily.

Daily thermal effectiveness (DTE) and average of relative thermal effectiveness (RTE) to different maize genotypes (Lu *et al.*, 2008).

$$RTE(I)=\left(\frac{T_i-T_b}{T_o-T_b}\right)^P\left(\frac{T_m-T_i}{T_m-T_o}\right)^{KP} \quad (7)$$

$$K=\frac{T_m-T_o}{T_o-T_b} \quad (8)$$

$$DTE=1/8\sum RTE(I) \quad (9).$$

Where, T_i = temperature of every time interval, T_b = cardinal temperature, T_0 = optimum temperature, T_m = maximum temperature, P = the temperature sensibility factor of maize which is a genetic coefficient was introduced to model.

The relative photoperiodic effect (RPE) to different maize genotypes (Huang *et al.*, 2004).

$$RPE=e^{-\left(\frac{DL-DL_O}{Ps}\right)^2} \quad (10).$$

RPE = relative photoperiodic effect, Ps = the photoperiod sensitive factor of maize which is a genetic coefficient was introduced to model. DL_O = the optimum duration of day, DL = the actual duration of day of the year. The equation as follow (Chen *et al.*, 2012a).

$$DL=12\times(1+(2/\pi\times \mathrm{asin}(a/b)) \quad (11)$$

$$a=\sin LAT\sin\sigma \quad (12)$$

$$b=\cos LAT\cos\sigma \quad (13)$$

$$\sin\sigma=-\sin(\pi\times23.45/180)\cos(2\pi\times(DAY-10)/365) \quad (14)$$

$$\cos\sigma=(1-\sin\sigma\sin\sigma)^{0.5} \quad (15).$$

Where, DL = the actual duration of day of the year, LAT = geographic latitude, σ = solar declination, DAY = Julian day series, which consider 1th Jan as 1, 2th Jan as 2, …, 31th Dec as 365.

The physiological development time(PDT) (Xu e*t al.*, 2006).

$$PDT(I)=\begin{cases}DTE\times IE\times RPE & 0<PDT\le PDT_{head}\\ DTE\times RPE & PDT_{head}<PDT\le PDT_{fill}\\ DTE\times FDF\times RPE & PDT_{fill}<PDT\le PDT_{matu}\end{cases} \quad (16)$$

$$PDT=\sum PDT(I) \quad (17).$$

Where, PDT = accumulative physiological development time, PDT(I) = daily relative physiological development time, PDT_{head} = physiological development time reach to jointing, PDT_{fill} = physiological development time reach to filling, PDT_{matu} = physiological development time reach to maturity. IE = basic earliness factor maize, which is a genetic coefficient was introduced to model, FDF = grouting factor which is a genetic coefficient was introduced to model.

The effect of nitrogen(NDF) (Chao and Luo, 2000)

$$NDF=1-(TANC-TCNP)/(TCNP-TMNC) \quad (18).$$

Where, $NDF<1$ as $TANC>TCNP$; $NDF=1$ as $TANC=TCNP$, this is the optimum nitrogen content of plant; $NDF>1$ as $TANC<TCNP$.

The critical nitrogen content(TCNP) of plant and the minimum nitrogen content(TMNC) of plant (Gu *et al.*, 1998):

$$TMNC_{(PDT)}=3.3802\times0.979^{PDT} \quad R^2=0.9042 \quad (19)$$

$$TCNP_{(PDT)}=(-0.09+1.1465SSNC_i)\times0.979^{PDT} \quad R^2=0.9480 \quad (20).$$

Where, $SSNC_i$ = the actual nitrogen content of maize seeding.

Results

Cardinal temperature, optimum temperature, maximum temperature (Table 2), optimum duration of day (9 h) and critical duration of day (16 h) of maize growth stages were confirmed by combining observed results in the present study, and by earlier studies.

Table 1: Geographical, climatological and pedologic situation of experimental fields

Field	Longitude and latitude	Annual average temperature (℃)	Sunshine duration	≥10℃Active accumulated temperature (℃)	Soil organic matter ($g·kg^{-1}$)	Soil alkali-hydrolyzable nitrogen ($mg·kg^{-1}$)	Soil available phosphorus ($mg·kg^{-1}$)	Soil rapid available phosphorus ($mg·kg^{-1}$)	Soil pH
A	43°63′N 122°25′E	6.1	3113h	3160	26.5	62.00	10.20	95.3	8.3
B	42°30′N 118°87′E	7.0	3060h	3200	13.04	68.46	12.48	104.2	8.1
C	40°56′N 110°53′E	7.5	3195h	3250	14.37	36.93	5.03	78.28	7.6

Table 2: The basic temperature parameter of different growth stages of maize

Stage of growing	CT	OT	MT
Sowing- Emergence	6	11	40
Emergence - Jointing	7	15	37
Jointing-Silking	9	21	39
Silking-Filling	16	24	33
Filling- Maturity	12	21	40

CT=Cardinal temperature; OT=Optimum temperature; MT= Maximum temperature

Daily thermal and photoperiodic effects of maize growth were calculated based on the above meteorological data and equation (1), (2). Then, the interaction of thermal and photoperiodic effect was used to calculate the daily physiological development effectiveness, integral of daily physiological development effectiveness which is physiological development time of maize. The integral value of physiological development effectiveness came from spike differentiation and phenophase stages were determined by data observed from the experiment 2 sown on May 11^{th}, which can get physiological development time of the different growth stages of maize. After calculation, the physiological development time for jointing, silking, filling and maturity from emergence was 22.8, 46.8, 55.4, 81.9 d, respectively and which reached growing tip lengthening of tassel, spikelet differentiation of tassel, floret differentiation stage of tassel and sexual organ development of tassel after 17.6, 21.5, 26.0, 32.8 d, respectively time to reach growing tip lengthening of ear, spikelet differentiation of ear, floret differentiation stage of ear and sexual organ development of ear was 22.5, 30.2, 32.6, 38.4 d, respectively.

Mechanism Model of Spike Differentiation and Phenophase was Constructed Based on Physiological Development Time Constant

Diurnal temperature and growing degree days: The major contributor of growth velocity was temperature during sowing to the emergence of maize. Temperature and illumination affect on the growth of maize after emergence 24 h of one day was divided into eight time intervals to make an exact calculation of the effect of temperature on physiological growth. The daily minimum, maximum temperatures and the temperature variation factor were used to calculate temperature and growing degree days (GDD) of time intervals of day using equations (3-6).

Table 3: Genetic coefficients of four types of maize genotypes

Genotypes	Temperature sensitivity	Photoperiod Sensitivity	Intrinsic earliness	Filling fraction
Jinshan27	0.28	9.82	0.83	0.67
Zhengdan958	0.31	9.76	0.88	0.66
Weike702	0.34	9.7	0.94	0.62
Xianyu335	0.36	9.68	0.96	0.61

Relative thermal effectiveness: The Bate function was used to calculate the relative thermal effectiveness of different time interval in one day. Daily thermal effectiveness (DTE) and average of relative thermal effectiveness (RTE) which calculated by T*emp* (i), cardinal, optimum and maximum temperatures using the equations (7-9).

Relative photoperiodic effect: As short-day crop, the critical duration day of maize is 16 h, with optimum duration day of 9 h. The Gaussian function was used to calculate the relative photoperiodic effect (RPE) as the equations (10-15).

Calculation of physiological development time: There are five growth stages of maize (sowing to emergence, emergence to jointing, jointing to silking, silking to filling and filling to maturity). The major contributor of growth velocity was temperature during sowing to emergence of maize. Temperature and illumination affect the growth of maize after emergence.

Results in present study indicated that emergence come up with the GDD accumulate to 145 d after sowing, when the depth of seeding was 3-5 cm.

The physiological development time after emergence was calculated using the equations (16-17). As preliminary estimate that the factor range was 0.8-1.0 (the late-maturing variety is 0.8, the precocious variety is 1.0), as preliminary estimate that the factor range was 0.6-1.0 (the variety with the lowest GDD is 0.6; the variety with the longest GDD is 1.0).

Nitrogen effect factor: Besides temperature and illumination, the growth of maize was effected by nutrient, especially nitrogen. The growth of maize was delayed with increasing nitrogen application within limits. The effect of nitrogen on maize was calculated using the equation (18).

Base data of experiment 2, there was a function relationship between the physiological development time and the critical nitrogen content of plant or the minimum nitrogen content of plant (Fig. 1), which was calculated using the equations(19-20).

Genetic coefficient and testing of model: Genetic coefficients were determined by data of experiment 2 sown at 11th May (Table 3).

Data from experiment 2 sown at 27th April, experiments 3 and 4 were used to test the model. Base on maize spike differentiation stages and physiological development time of phenophase inversed to simulative date (days after sowing), compared observed value and simulative value, and made statistical analysis of conformity between observed value and simulative value by RMSE.

Results showed the predication deviation range of model was from 0-3 d on maize spike differentiation stages, and that of RMSE was from 1.06- 1.34 d. The predication deviation was comparatively low on growing tip lengthening stage and floret differentiation of tassel. However, it was relatively high on spikelet differentiation stage of both tassel and ear (Table 4).

The predication deviation of model for emergence was low, the range of model was from 0-1 d, and of RMSE was 0.71 d. The predication deviation of model for jointing was greater; the range of model was from 0-4 d and of RMSE was 1.50 d (Table 5).

The predication deviation of model for maturity was low, the range was from 0 to 2 d and of RMSE was 1.0 d; which for filling was greater, with range from 1 to 4 d and of RMSE was 1.65 d (Table 6).

The predication deviation of model for growth stages in different maize genotypes in Salaqi are presented in Table 7. The predication deviation of model for emergence was low, the range was from 0 to 1 d that of RMSE was 0.71 d; which for jointing was greater, the range was from 0-4 d, and that of RMSE was 1.51 d.

Results from different experimental locations for stages of seeding, elongation, silking, grain filling, maturity, growing tip lengthening, spikelet differentiation, floret differentiation and sexual organ development demonstrated absolute simulation error of 0-5 d, and the root mean square error less than 3.5 d. For the simulation of growth stages, predictions of emergence and maturity got better, however, the prediction of jointing was poor. For maize spike differentiation stages, the prediction of growing tip lengthening and sex organ development stages; however, the prediction of spikelet differentiation stage was poor. These indicated that the basic temperature parameters of growth and model parameter of present model need further adjustments.

The diagrams of relationship between observed and simulated values of growth and spike differentiation stages showed that the observed values had good coherence to simulated values (Figs. 2-4).

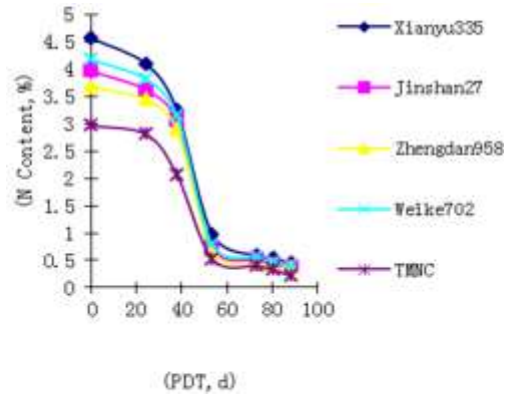

Fig. 1: Change in critical nitrogen contents of different maize varieties and minimum nitrogen content of maize with the accumulation of physiological development time

Note: Gro = Growing tip lengthening stage, Spi = Spikelet differentiation stage, Flo = Floret differentiation stage, Sex = Sex organ development stage

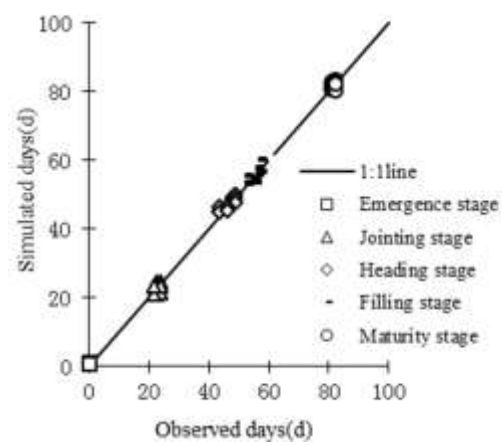

Fig. 2: Comparison of simulated and observed calendars on the growing stage of different genotypes, sowing dates and test area of maize in 2012

Note: Gro = Growing tip lengthening stage, Spi = Spikelet differentiation stage, Flo = Floret differentiation stage, Sex = Sex organ development stage

Discussion

Calculation of the thermal and photoperiodic effects has been the major content of the model during the model construction stage. The model of thermal effect was expressed by linearity and non-linearity. Nonlinear function includes Richards function, Logistic function, trigonometric function, Gaussian function and Beta function. The Beta function was used in many studies for its unique advantage which could reflect the effects of temperature on crop growth those are the optimum temperature for the rapid development of crop and the minimum and maximum temperature of stunt development, the response characteristic of developmental rate on temperature, and

Table 4: Prediction deviation for ear and tassel growth stages in different maize genotypes in Tongliao (d)

Genotypes	Growing tip lengthening stage		Spikelet differentiation stage		Floret differentiation stage		Sex organ development stage	
	Tassel	Ear	Tassel	Ear	Tassel	Ear	Tassel	Ear
Jinshan27	+2	+1	+2	-3	+1	+2	+2	+2
Xianyu335	+1	0	+2	0	-2	0	+1	-1
Zhengdan958	0	-2	+2	0	0	-1	0	0
Weike702	0	-1	+1	+2	0	+2	-1	-1
RMSE	1.06	1.11	1.34	1.34	1.06	1.22	1.11	1.11

the biological parameter of crop development (Yin, 1994; Zheng, 1999; Lu *et al.,* 2008). According to Gao *et al.* (1989) for thermal effect of rice growth, and established a "rice clock model" which could simulate combined influence of duration of day and temperature day by day; however, the applicability of this model was limited for it could not ensure the precondition that development rate was the fastest with the predesigned optimum temperature. Therefore, the special shape of Beta function $f(T)=(\frac{T-T_b}{T_o-T_b})^P(\frac{T_m-T}{T_m-T_o})^{kP}$ ($k=\frac{T_m-T_o}{T_o-T_b}$) was used to express the thermal effect of crop (Lu *et al.*, 2008). In the present study, the special shape of Beta function was used to express maize thermal effect and gained a preferable simulation.

For photoperiodic effect, the quadratic function (Yan, 2000; Liu *et al.*, 2004) and trigonometric function (Zou *et al.*, 2009) were used to represent the long day plant of wheat, barley and linear function (Zhang *et al.*, 2003) and exponential function (Gao *et al.*, 1989) were used to represent the short day plant (cotton, rice and maize).

In present study, Gaussian function $e^{-(\frac{DL-DL_O}{PS})^2}$ was used to calculate the photoperiodic effect of maize, PS means photoperiod sensitivity. The equation shows that the Gaussian function is a decreasing function that the value of photoperiodic effect and the growth rate decreased with increasing duration of day. The value of photoperiodic effect increased with increasing PS, which means the effect of illumination on growth decreasing and this is consistent with the real situation of the effect of illumination on the growth of maize. Therefore, the photoperiodic effect could be represented by Gaussian function, and was proved by the inspection result of the present study.

The physiological development time reflects the intrinsic attribute of basic development factors and reflects effect of temperature and illumination on the crop growth at the same time. The physiological development time necessary to complete a development stage in a particular genotype remains essentially constant under any temperature and illumination conditions (Chao and Luo, 2000). Therefore, the physiological development time constant theory was used to construct the model of growth. In the present study, maize spike differentiation and growth model was constructed, and with genetic parameters (temperature sensitivity, photoperiod sensitivity, intrinsic earliness and filling fraction) were imported to express genetic differences of maize growth. The test results in different locations showed that the model had a great predictability and reliability.

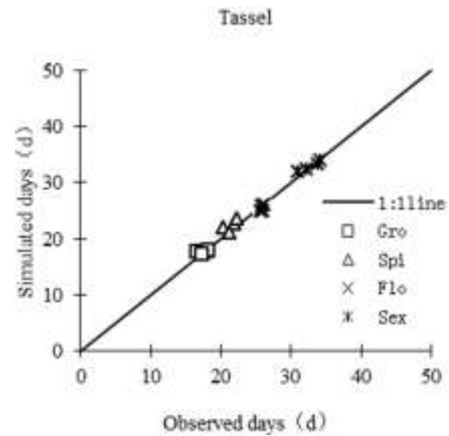

Fig. 3: Comparison of simulated calendar and calendars for tassel differentiation growing stages with different genotypes and sowing dates of maize in 2012 at Tongliao
Note: Gro = Growing tip lengthening stage, Spi = Spikelet differentiation stage, Flo = Floret differentiation stage, Sex = Sex organ development stage

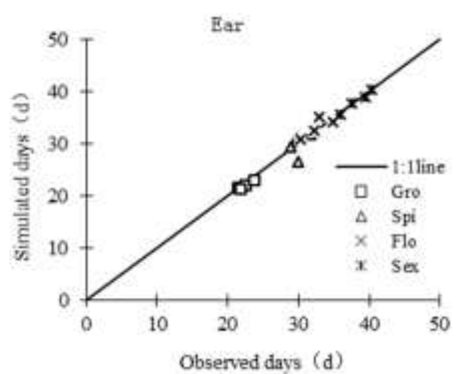

Fig. 4: Comparison of simulated and observed calendar for ear differentiation growing stages with different genotypes and sowing dates of maize in 2012 at Tongliao
Note: Gro = Growing tip lengthening stage, Spi = Spikelet differentiation stage, Flo = Floret differentiation stage, Sex = Sex organ development stage

Nitrogen is a critical limiting element for plant growth, and how plant growth reacted to the nitrogen application is

Table 5: Prediction deviation for growth stages in different maize genotypes in Tongliao (day)

Genotypes	Emergence	Jointing	Silking	Filling	Maturity
Jinshan27	0	+4	+2	+3	0
Xianyu335	0	0	+2	+1	0
Zhengdan958	-1	0	+1	0	1
Weike702	0	2	+1	+1	3
RMSE	0.71	1.50	1.26	1.29	1.26

Table 6: Prediction deviation for growing stage of different maize genotypes in 2012 at Chifeng (day)

Genotypes	Emergence	Jointing	Silking	Filling	Maturity
Jinshan27	0	-1	0	-1	0
Xianyu335	2	0	+3	+3	0
Weike702	-2	-4	0	+4	-2
Zhengdan958	0	-2	+1	+2	0
RMSE	1.19	1.51	1.26	1.65	1.00

Table 7: Prediction deviation for growth stages in different maize genotypes in 2012 at Salaqi (day)

Genotypes	Emergence	Jointing	Silking	Filling	Maturity
Jinshan27	-1	+4	-1	-3	0
Xianyu335	0	+1	+2	0	+3
Weike702	0	0	-2	-1	+1
Zhengdan958	0	+2	-1	-1	+2
RMSE	0.71	1.51	1.26	1.29	1.37

an important standard for measuring the model integrity. At present, most of the model imports the minimum, critical and the actual nitrogen concentration of plant to express effect of nitrogen on the crop growth. The critical nitrogen concentration is the minimum nitrogen concentration that plant reach the maximum dry matter (Liu, 2000), the minimum nitrogen concentration is the concentration which could fit the need of the plant growth. Limited by the research conditions, it is hard to test the minimum nitrogen concentration in the actual production. Therefore, in present study, the nitrogen concentration of the maize was fertilized with 0 kg ha^{-1} nitrogen as the minimum nitrogen concentration was considered same level for different maize varieties.

The critical nitrogen concentration was different with different maize varieties. In the previous study, multinomial quantic was used to express the relationship between PDT and the critical and minimum nitrogen concentration (Zheng, 1999), this model appeared more complex and empirical component and did not distinguish the differences of critical nitrogen concentrations among different maize varieties. In the present study, the exponential function was used to express the relationship between PDT and the critical and the minimum nitrogen concentration, which simplified the relationship between them, and made the model easy to use. The result of the critical nitrogen concentration in different maize varieties was calculated by the actual nitrogen concentration in plant sampled during the seeding stage indicated the nitrogen effect in the current model is reliable. Only four maize varieties were used to simulate the spike differentiation and phenophase, and parameters of the model were of preliminary nature in the present study. This model need more debugging and optimizing, and tested by more varieties and more locations. Water is a major effect factor on plant growth. Hence, how to construct the model for maize spike differentiation and phenophase based on water and fertilizer applications will be the next step.

Conclusion

Results demonstrated that the absolute simulation error on growth stage (including emergence, jointing, silking, filling and maturity) and tassel and ear differentiation stages (including growing tip lengthening, spikelet differentiation, floret differentiation stage and sexual organ development) in different maize cultivars were between 0–5 d, and the root mean square error was less than 3.5 d. This model clearly demonstrated that the mechanism is rational and practical.

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