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Research Article

# Predicting Physiological Growth Period based on Cumulative Climatic Suitability of Spring Maize

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**Abstract**

The growth period prediction at the various physiological stage of spring maize is an essential component in agricultural management decisions. An Improved Climate Suitability (ICS) model was established by integrating temperature, precipitation, sunshine and soil moisture and setting individual weight coefficient in each subordinate function according to the observation data of spring maize growth and meteorological factors of 14 agrometeorological stations in the Liaoning Province of northeast China from 1981 to 2010. The predicted value ($B_{jk}$) and reference value ($B_k$) of the cumulative climatic suitability index were calculated by the ICS model for arranging farming activities in advance when the $B_{jk}$>$B_k$ at the various physiological growth stage of spring maize. The ICS model was further verified by the observation data at the whole and various physiological stages of spring maize. The result showed that the $B_{jk}$ was linearly correlated with the observed days at each physiological growth stage of spring maize with $R^2$ of 0.75-0.88, $P$<0.001, Thus, the $B_{jk}$ can be used to determine the growth period of the various physiological stage of spring maize. The prediction days were significantly correlated with the observed days at the whole and each physiological growth stage of spring maize ($R^2$ of 0.57-0.98, $P$<0.001) with the absolute error (ABSE) of 1.1-4.1 d. Thus, the precision of the ICS model is acceptable for forecasting the growth period and arranging farming activities in advance. Thus, the ICS model should be promoted further in the management of spring maize plantation.

**Keywords:** Climatic suitability model; Spring maize; Forecast; Physiological growth period; Agricultural management decision

## Introduction

The crop growth is proceeding with the variation of the morphological and physiological characteristics at each physiological period, which can be regarded as an indicator of climate change [1]. The length of the physiological growth period is closely related to both crop genetic trait and climate factors [2,3]. Thus, to clarify the relationship between the pattern of the crop growth period and climate factors is critical for the optimization of farming system, multi-cropping index, irrigation and drainage plan and crop variety layout.

The crop growth period at each physiological stage can be used as a time marker to reflect the crop development process, and it is also the simulation basis of crop dry matter accumulation and distribution, nutrient absorption and transfer, yield and quality [4,5]. Reanmar firstly found that plants need the same accumulated temperature to complete a certain development period, i.e., Growing Degree Days (GDD) in 1735 by crop development modeling. The Growing Degree Days (GDD) as a climatic feature has vastly improved the prediction of phenological events compared with other approaches for crop phenology and developmental stage [6]. The plant phenology models were applied for the prediction of primary productivity, the occurrence of atmospheric pollen and the impact of global change on the phenology since 1963 [7]. The Physical Development Time (PDT) model for development period simulation was also put forward by referring to genotype variety and the constant time required for the crop to complete a physiological stage under the optimal temperature and light conditions [8]. The PDT model takes into account the thermal effect, photoperiodic effect and the differences among varieties, which overcomes the limitation of the GDD model that only considering the temperature. However, the PDT model does not include the influence of water conditions on crop development. The Climate Suitability (CS) model was applied to the prediction of crop development period by considering light, temperature and water [9]. The temperature, moisture and light were regarded as three fuzzy sets for comprehensively evaluating the influence of multiple factors by constructing the subordinate function and setting the weight coefficient of a single factor with the principle of fuzzy transformation. Thus, the CS model can objectively reflect the satisfaction of climate conditions to crop growth and development.

Spring maize is the primary grain crop in Liaoning Province, and its planting area accounted for 2.18×10$^4$ hm$^2$ about 6% of China in 2017 [10]. The analysis of the influence of meteorological conditions on spring maize production has always been one of the essential meteorological services. In this study, we predicted the period of 9 stage of physiological development (i.e., sowing to germination (SOW), germination to trefoil (GER), trefoil to 7 leaves (TRE), 7 leaves to jointing (7LE), jointing to tasseling (JOI), tasseling to flowering (TAS), flowering to silking (FLO), silking to milk (SIL), milk to maturation (MIL)) of three maturity types of spring maize by an improved climatic suitability (ICS) model in Liaoning Province,




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China. The ICS model was improved by setting individual weight coefficients and newly added subordinate function of soil moisture for farming management decisions of spring maize plantation.

## Materials and Methods

### Study area

Liaoning Province is located in northeastern China (118°50'E -125°47'E, 38°43'N -43°29'N) with the area of 14.8×10⁴ km². The region is characterized by a temperate continental climate with an average annual temperature of 5.2-10.9 °C, annual precipitation of 445-1067 mm and a frost-free period of 131-223 d [11]. The spring maize planted in the region exceeded 2.0×10⁴ km² since 2016. Typically, spring maize is planted in spring (mid to late April-early May) and harvested in autumn (October), with only one planting season per year [12].

### Data

The daily meteorological variables, such as average daily air temperature, total precipitation, sunshine hours, soil moisture were obtained from 14 agricultural meteorological stations at Haicheng, Wafangdian, Benxixian, Chaoyangxian, Suizhong, Xinmin, Xiuyan, Zhuanghe, Kuandian, Heishan, Fuxinxian, Zhangwu, Jianchang, Changtu in Liaoning Province from 1981 to 2010 (Figure 1). The information on meteorological variables was provided by the National Meteorological Information Center of China (Table S1).

### Study method

The agricultural climate factors significantly influence the growth, development, and yield of spring maize. Here, four climatic factors, such as light, temperature, precipitation and soil moisture that play a crucial role in spring maize growth in the northeast of China, were mainly considered in this study. The growth period of spring maize was divided into 9 stages: sowing to germination (SOW), germination to trefoil (GER), trefoil to 7 leaves (TRE), 7 leaves to jointing (7LE), jointing to tasseling (JOI), tasseling to flowering (TAS), flowering to silking (FLO), silking to milk (SIL), milk to maturation (MIL).

Based on the comprehensive climate suitability model (Eq.1), the daily climate suitability index (F(C)) of each physiological development stage of spring maize was calculated using the meteorological data of 14 meteorological stations from 1981 to 2010. The average cumulative climate suitability ($B_k$, Eq. 14) at the


**Figure 1:** Agricultural meteorological stations in the Liaoning Province of China.

various development stage in the past 30 years was regarded as the reference value for forecasting the development period. When the cumulative climate suitability ($B_{jk}$, Eq.13)>$B_k$ at any development stage, the next development stage can be judged. The ICS model was tested with the data at 14 meteorological stations from 1981 to 2010, and the correlation was analyzed between the prediction days and the observed days. The ABSE was used to test the prediction accuracy of the model. The modeling program was performed with R 2.11.1, C# software and IBM SPSS Statistics 20 (SPSS Inc, Chicago, IL, USA).

### Data analysis

The climate factors and maize growth period were analyzed with C# software for the subordinate climate suitability models. Based on the meteorological variables and the yield of spring maize, the weight coefficients for temperature (T), precipitation (P), sunshine (S), soil moisture (W) were determined in IBM SPSS Statistics 20 (SPSS Inc, Chicago, IL, USA). The prediction of the growth period of spring maize was carried out using R 2.11.1. Figures were drawn using SigmaPlot 10.0 and ArcGIS 10.2.2 software.

## Results

### Modeling

Based on the weighted average method, a comprehensive suitability evaluation model was established by considering the demand for temperature, precipitation, sunshine, and soil moisture conditions in the various development stages of spring maize. The function was as follows:

$$F(C)_i = aF(T)_i + bF(P)_i + cF(S)_i + dF(W)_i \quad (1)$$

where $F(C)_i$ is the comprehensive suitability index for the day $i$ of each growth stage of spring maize, and $a$, $b$, $c$, and $d$ are the weight coefficients that were calculated according to Eq.(9-12). $F(T)$ is the subordinate function of temperature; $F(P)$ is the subordinate function of precipitation; $F(S)$ is the subordinate function of sunshine; $F(W)$ is the subordinate function of soil moisture. The subordinate functions of T, P, S and W based on fuzzy mathematics during the growth periods of spring maize are established.

**Subordinate function of temperature:** The effect of temperature on maize growth and development was quantitatively assessed by considering the optimum, minimum and maximum temperature in the process of maize life activity. The subordinate function for temperature was defined in fuzzy mathematics as follows [13]:

$$F(T)_i = \begin{cases} 0 & T_i \le T_l \ or \ T_i \ge T_h \\ \dfrac{(T_i - T_l)\times(T_h - T_i)^B}{(T_0 - T_l)\times(T_h - T_0)^B} & T_l < T_i < T_h \ and \ T_i \ne T_0 \\ 1 & T_i = T_0 \end{cases} \quad (2)$$

$$B = \frac{T_h - T_0}{T_0 - T_l} \quad (3)$$

where $F(T)_i$ is the temperature suitability index of spring maize. $T_i$ is the average temperature during the spring maize growing season. $T_h$, $T_l$, $T_0$ are the upper limit, the lower limit and the optimum of growth temperature for spring maize, respectively (Table 1). B is a constant. $T_h$, $T_l$, $T_0$ were listed in Table 1.

**Subordinate function of precipitation:** According to the evaporation and water requirement at the various growth stage of

**Table 1:** $T_h$, $T_l$, $T_0$ at each growth stage of spring maize (°C). $T_h$, $T_l$, $T_0$ are the upper limit, the lower limit and the optimum of growth temperature for spring maize, respectively. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

| Variable | Growth stage of spring maize | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SOW | GER | TRE | 7LE | JOI | TAS | FLO | SIL | MIL |
| $T_l$ | 5 | 6 | 8 | 10 | 14 | 16 | 16 | 16 | 14 |
| $T_0$ | 10 | 12 | 15 | 20 | 23 | 24 | 24 | 24 | 22 |
| $T_h$ | 22 | 25 | 30 | 34 | 35 | 33 | 33 | 33 | 32 |

spring maize, the precipitation suitability index was calculated to assess the precipitation of spring maize in the Liaoning Province as follows [14]:

$$F(P)_i = \begin{cases} 1-\dfrac{|\Delta W_i|}{W_i} & P_i < W_i \\ 1 & P_i \geq W_i \end{cases} \quad (4)$$

$$\Delta W_i = P_i - W_i \quad (5)$$

$$W_i = K_c \times ET_{oi} \quad (6)$$

where $F(P)_i$ is the precipitation suitability index of spring maize. $W_i$ is the water surplus-deficit. $W_i$ is the physiological water requirement of spring maize. $P_i$ is the precipitation in the specific growth period of spring maize. $K_c$ is the crop coefficient that depended on the growth stage of spring maize (Table S2). $ET_{oi}$ is the reference evapotranspiration calculated using the Penman-Monteith formula (FAO) [15].

**Subordinate function of sunshine:** The growth morphogenesis and yield of spring maize depended on the sunshine intensity that can control the growth and assimilation of spring maize. The available sunshine will be suitable for spring maize growth when the sunshine hours >70% of the possible duration. Thus, the sunshine suitability index was expressed of spring maize in the Liaoning Province as [16]:

$$F(S)_i = \begin{cases} e^{-[(S-S_0)/b]^2} & S < S_0 \\ 1 & S \geq S_0 \end{cases} \quad (7)$$

where $F(S)_i$ is the sunshine suitability index. $S$ is the actual sunshine time. $S_0$ is total sunshine hours when the possible duration>70% (Table S3). $b$ is a constant (Table 2).

**Subordinate function of soil moisture:** The subordinate function of soil moisture was expressed at each growth stage as follows [14]:

$$F(W)_i = \begin{cases} e^{-((SM-SM_1)/b_1)^2} & SM_b \leq SM < SM_1 \\ 1 & SM_1 \leq SM < SM_2 \\ e^{-((SM-SM_2)/b_2)^2} & SM_2 < SM \leq SM_m \\ 0 & SM > SM_m \text{ or } SM < SM_b \end{cases} \quad (8)$$

where $F(W)_i$ is soil moisture suitability index; $SM$ is the measured soil moisture; $SM_b$ and $SM_m$ are the minimum (40% gravimetric moisture) and the maximum soil moisture (100%) that could be tolerated for spring maize growth, respectively; $SM_1$ and $SM_2$ are the corresponding lower and upper limits (60% and 90%) of soil moisture that are suitable for spring maize growth. The constants $b_1$ and $b_2$ are 12 and 6, respectively.

**Table 2:** $b$ at each growth stage of spring maize. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

| Variables | Growth Stage of spring maize | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SOW | GER | TRE | 7LE | JOI | TAS | FLO | SIL | MIL |
| b | 4.77 | 4.77 | 4.77 | 5.08 | 5.17 | 5.14 | 5.14 | 5.14 | 5.24 |

**Table 3:** Weight coefficient of subordinate function at each physiological growth stage of maize growth. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

| Growth Stages | Maturity types | a | b | c | d |
|---|---|---|---|---|---|
| SOW | mid | 0.25 | 0.3 | 0.24 | 0.22 |
| | later | 0.05 | 0.43 | 0.21 | 0.31 |
| | latest | 0.13 | 0.32 | 0.35 | 0.21 |
| GER | mid | 0.32 | 0.37 | 0.27 | 0.03 |
| | later | 0.03 | 0.14 | 0.22 | 0.61 |
| | latest | 0.4 | 0.41 | 0.05 | 0.15 |
| TRE | mid | 0.35 | 0.4 | 0.01 | 0.24 |
| | later | 0.27 | 0.15 | 0.1 | 0.48 |
| | latest | 0.08 | 0.05 | 0.47 | 0.41 |
| SEV | mid | 0.09 | 0.58 | 0.15 | 0.19 |
| | later | 0.4 | 0.2 | 0.12 | 0.28 |
| | latest | 0.39 | 0.11 | 0.06 | 0.45 |
| JOI | mid | 0.34 | 0.46 | 0.08 | 0.12 |
| | later | 0.36 | 0.29 | 0.23 | 0.12 |
| | latest | 0.38 | 0.23 | 0.32 | 0.08 |
| TAS | mid | 0.33 | 0.26 | 0.06 | 0.35 |
| | later | 0.34 | 0.32 | 0.04 | 0.31 |
| | latest | 0.16 | 0.24 | 0.3 | 0.3 |
| FLO | mid | 0.28 | 0.43 | 0.05 | 0.25 |
| | later | 0.34 | 0.25 | 0.24 | 0.17 |
| | latest | 0.18 | 0.07 | 0.44 | 0.31 |
| SIL | mid | 0.09 | 0.72 | 0.13 | 0.06 |
| | later | 0.36 | 0.35 | 0.22 | 0.07 |
| | latest | 0.18 | 0.41 | 0.14 | 0.26 |
| MIL | mid | 0.29 | 0.01 | 0.3 | 0.4 |
| | later | 0.36 | 0.32 | 0.09 | 0.22 |
| | latest | 0.13 | 0.65 | 0.05 | 0.18 |

## Weight coefficients of the subordinate function

The weight coefficients of each subordinate function (a, b, c, d) are equal to their path coefficients divided by the sum of the path coefficients of T, P, S and W (Table 3). $a + b + c + d = 1$. The subscripts of T, P, S, W represent temperature, precipitation, sunshine, and soil moisture, respectively. The path coefficient was calculated by the correlation between each suitability index and the yield of spring maize at the various growth stage.

$$a = \frac{|a_T|}{|a_T|+|a_P|+|a_S|+|a_W|} \quad (9)$$

$$b = \frac{|a_P|}{|a_T|+|a_P|+|a_S|+|a_W|} \quad (10)$$

$$c = \frac{|a_S|}{|a_T|+|a_P|+|a_S|+|a_W|} \quad (11)$$

$$d = \frac{|a_W|}{|a_T|+|a_P|+|a_S|+|a_W|} \quad (12)$$

## Dynamic forecast model of the physiological growth period

Based on the daily climate suitability (Eq.1), the cumulative climate suitability ($B_{jk}$) of spring maize was calculated at each physiological growth period. The cumulative climate suitability was regarded as the indicator of the physiological development of spring maize. The $B_{jk}$ at each stage are as follows [17]:

$$B_{jk} = \sum_{i=1}^{m} F(C)_i \quad (13)$$

where $B_{jk}$ is the cumulative climate suitability index at $k$ stage in $j$ year; $m$ is the duration of each physiological growth stage (days); $i$ is the day from 1 to m in the $k$ stage (day); The reference value ($B_k$) of cumulative climatic suitability index ($B_k = \frac{1}{n}\sum_{j=1}^{n} B_{jk}$, Eq.14), which represents the average physiological index at each physiological development stage calculated from 1981 to 2010 (n=30 year, Table 4). When the $B_{jk} > B_k$ at any physiological growth stage, the next physiological growth stage can be forecasted. The $B_{jk}$ was linearly correlated with the observed days at each physiological growth stage of spring maize in the past 30 years (Figure 2, $P$<0.001).

## Testing the model

The growth period of spring maize at the physiological growth stage of spring maize was predicted using the ICS model at 14 agricultural meteorological stations from 1981 to 2010 (Figure 3). A linear relationship between the predicted and observed values was found with the correlation coefficient ($R^2$) of 0.57-0.98 with $P$<0.001 (Table 5). The $R^2$ was relatively low at Milk (0.57) and Maturation (0.61) stage, while much higher at Trefoil, Flowering, Silking and the whole growth period of spring maize (>0.90). The absolute errors (ABSE) between the predicted and observed values were 1.1-4.1 d across 9 physiological growth stages (Table 6). The ABSE of GER, TAS, and FLO were less than 1.8 d. The JOI stage of the latest maturity type of spring maize was slightly high with ABSE of 4.1 d. The ABSE was used to analyze the consistency and accuracy between the predicted days and the observed days as follows:

$$ABSE = \frac{1}{n}\sum_{i=1}^{n} |P_i - O_i| \quad (14)$$

where $P_i$ is the predicted value, $O_i$ is the observed value, and $n$ is the sample size.

**Table 4:** $B_k$ of each physiological growth stage of spring maize at 14 meteorological stations in Liaoning Province. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

| Station | SOW | GER | TRE | 7LE | JOI | TAS | FLO | SIL | MIL |
|---|---|---|---|---|---|---|---|---|---|
| Haicheng | 5.4 | 3.63 | 10.26 | 8.65 | 14.34 | 1.89 | 1.52 | 16.85 | 16.04 |
| Wafangdian | 9.84 | 2.97 | 15.31 | 11.12 | 13.34 | 3.62 | 1.46 | 15.48 | 18.6 |
| Benxixian | 9.25 | 4 | 9.18 | 17.37 | 15 | 2.28 | 1.49 | 13.89 | 16.31 |
| Chaoyangxian | 7.11 | 2.93 | 6.55 | 13.45 | 13.76 | 2.19 | 1.49 | 19.09 | 21.15 |
| Suizhong | 7.16 | 3.05 | 14.36 | 15.56 | 14.1 | 3.03 | 1.56 | 10.95 | 19.19 |
| Xinmin | 10.27 | 2.6 | 10.13 | 10.99 | 12.29 | 1.97 | 1.43 | 14.25 | 17.59 |
| Xiuyan | 9.08 | 3.39 | 8.34 | 15.91 | 17.72 | 1.82 | 1.17 | 12.98 | 13.12 |
| Zhuanghe | 9.52 | 3.73 | 11.57 | 15.81 | 13.14 | 1.19 | 1.78 | 12.24 | 17.27 |
| Kuandian | 8.27 | 4.58 | 14.73 | 14.45 | 17.21 | 1.4 | 0.79 | 18.06 | 13.15 |
| Heishan | 10.03 | 4.09 | 11.42 | 13.34 | 19.69 | 2.81 | 1.59 | 19.88 | 16.45 |
| Fuxinxian | 10.61 | 3.55 | 8.06 | 23.42 | 16.04 | 3.04 | 2 | 22.07 | 8.8 |
| Zhangwu | 12.16 | 3.71 | 11.87 | 18.21 | 15.69 | 2.34 | 1.79 | 21.61 | 20.06 |
| Jianchang | 6.7 | 3.51 | 13.47 | 16.36 | 12.58 | 1.82 | 2.01 | 22.17 | 9.79 |
| Changtu | 13.86 | 4.8 | 11.35 | 13.83 | 18.92 | 1.76 | 1.75 | 10.86 | 13.25 |

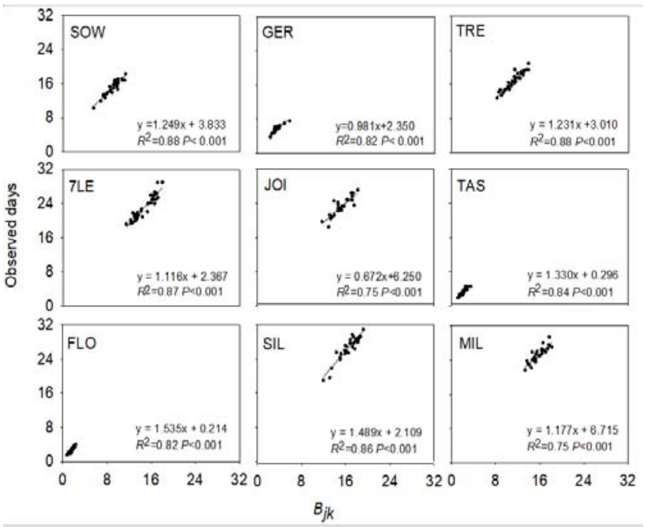


**Figure 2:** The relationship of $B_{jk}$ with the observed days at each physiological growth stage of spring maize. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

**Table 5:** Observed days and predicted days at the physiological growth period of spring maize. $R^2$: correlation coefficient, $P$: significant level. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

| No. | Physiological growth period | $R^2$ | $P$ |
|---|---|---|---|
| 1 | Germination | 0.79 | <0.001 |
| 2 | Trefoil | 0.93 | <0.001 |
| 3 | 7 leaves | 0.81 | <0.001 |
| 4 | Jointing | 0.7 | <0.001 |
| 5 | Tasseling | 0.7 | <0.001 |
| 6 | Flowering | 0.9 | <0.001 |
| 7 | Silking | 0.94 | <0.001 |
| 8 | Milk | 0.57 | <0.001 |
| 9 | Maturation | 0.61 | <0.001 |
| 10 | The whole | 0.98 | <0.001 |

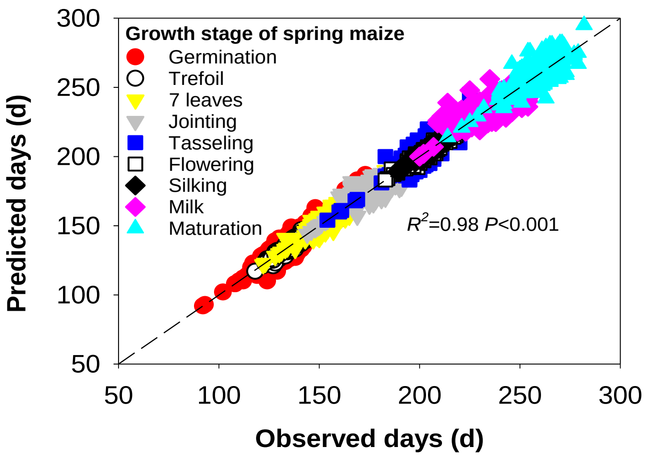


**Figure 3:** Observed days and predicted days at the whole physiological growth period of spring maize.

**Table 6:** The ABSE between the predicted and observed values at each physiological stage of three maturity types of spring maize. SOW: sowing to germination, GER: germination to trefoil, TRE: trefoil to 7 leaves, 7LE: 7 leaves to jointing, JOI: jointing to tasseling, TAS: tasseling to flowering, FLO: flowering to silking, SIL: silking to milk, MIL: milk to maturation.

| Maturity type of spring maize | Physiological stage of spring maize | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SOW | GER | TRE | SEV | JOI | TAS | FLO | SIL | MIL |
| Mid | 2.9 | 1.8 | 2.9 | 3.2 | 3.7 | 1.4 | 1.4 | 3.4 | 2.8 |
| Later | 3.4 | 1.6 | 2.8 | 3.4 | 2.8 | 1.5 | 1.2 | 3.5 | 3.7 |
| Latest | 3.6 | 1.8 | 2.4 | 2.9 | 4.1 | 1.4 | 1.1 | 3.6 | 3.8 |

## Discussion

### Climate variable in the model

The comprehensive climate suitability that combined with multi-climate factors was helpful for predicting the physiological growth of spring maize. Spring maize may alter the period at each physiological growth stage to adapt to climate change [18]. The increasing temperature may shorten the growth period and reduce the yield of spring maize [19,20]. Moreover, the accelerated phenology may change the maximum water requirement and prevent the pollination process of spring maize [21]. Based on the effective accumulated temperature, the crop growth period model was recently constructed for predicting crop development period [22]. The effect of climate change on crop growth periods was simulated using a temperature-dependent nonlinear function [23]. However, the spring maize growth period was related to many climate factors, such as temperature, precipitation, sunshine and soil moisture. Soil moisture is a critical variable that should be considered for evaluating climate suitability. On the one hand, the leaves of spring maize can rapidly uptake water in the short-term during the rainfall. On the other hand, the rainfall process may result in the difference of soil moisture. Thus, soil water was differentially absorbed and utilized by spring maize root due to the distinct soil properties. Further, the climate factors of temperature, precipitation and sunshine were involved in the integrated Climatic Suitability (CS) model for crop growth prediction [24]. However, soil moisture as a critical factor that influences the crop growth was not considered in the CS model. Thus, an improved CS model by adding the function of soil moisture and weight coefficients was established in this study.

### Period prediction at each physiological growth stage of spring maize

The maturity varieties of spring maize in Liaoning Province were categorized as mid-, later- and latest- maturation by the response of the whole growth period to climate change (Table S4). The tillage of spring maize was improved by adjusting the sowing dates of maize maturity types for prolonging the growth period in agricultural production [25]. The inconsistent effect of meteorological factors on the climate suitability of the physiological growth was found at different growth stages of spring maize [13,26]. However, the climate suitability model was usually evaluated in the whole growth period, but rarely considering at different the growth stages [27].

The growth period of spring maize at each and the whole physiological growth stage of spring maize was forecasted by the ICS model in this study. A linear relationship between the predicted and observed values at various physiological growth period was found with the correlation coefficient ($R^2$) of 0.57-0.98 with $P$<0.001 (Table 5). The $R^2$ was relatively low at Milk (0.57) and Maturation (0.61) stage, while much higher at Trefoil, Flowering, Silking and the whole growth period of spring maize (>0.90). The absolute errors (ABSE) between the predicted and observed values were 1.1-4.1 d across 9 physiological growth stages (Table 6). The ABSE of GER, TAS, and FLO were less than 1.8 d that much lower than those of the others. The JOI stage of the latest maturity type of spring maize is slightly worse with ABSE of 4.1 d. Thus, the ICS model can be applied to forecast the growth period at the whole and most physiological stage of spring maize in Liaoning Province for the agrometeorological service. The effect of extreme meteorological conditions, such as hail, wind, and heavy rain, on maize growth, is not elucidated in this study. Therefore, further researches should focus on the effect of the meteorological disaster on the growth period prediction in the ICS model.

## Conclusions

The ICS model was constructed by setting individual weight coefficients and newly added subordinate function of soil moisture by using 30 years of agricultural meteorological observation data from 1982 to 2010 in Liaoning Province of northeast China. The growth period at the whole and each physiological stage of spring maize was predicted by the ICS model on a daily basis. The parameters of the subordinate function of temperature, precipitation, sunshine and soil moisture were further adjusted according to the actual data at each physiological growth period of spring maize. The accuracy of the model was fully satisfied with the need in the agrometeorological forecast. Therefore, the ICS model can be applied to forecast the growth period at the whole and each stage of spring maize in Liaoning Province of northeast China.

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## Author Contributions

Bin Zhou did this experiment and wrote this paper; Junjie Lin designed and revised the paper; Yushu Zhang and Ji Li finished the field investigation; Ting Wang and Dongming Liu did statistical analysis and modeling.

## Data Availability Statement

All data are contained within the manuscript and its appendices.

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