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Analysis of characteristics of rice tillering dynamics influenced by sowing dates based on DTM

Xiaohui Wang [a,b], Dang Zou [c], Can Li [d], Wei Zhou [e], Kefu Li [f], Qiyuan Tang [a], Xinghui Zhu [a], Xumeng Li [a,*], Leping Cao [g]

[a] College of Agronomy, Hunan Agricultural University, Changsha, Hunan, 410128, China
[b] College of Information and Intelligence Sciences, Hunan Agricultural University, Changsha, Hunan, 410128, China
[c] Hengyang Academy of Agricultural Sciences, Hengyang, Hunan, 421200, China
[d] Agriculture and Rural Bureau of Ningyuan County, Ningyuan, Hunan, 425600, China
[e] Hunan Arts and Crafts Vocational College, Yiyang, Hunan 413000, China
[f] Guohao Academy, Tongji University, Shanghai, 200092, China
[g] Hunan Biological And Electromechanical Polytechnic, Changsha, 410127, China

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ABSTRACT

To quantitatively analyze the regularity and characteristics of tillering dynamics of rice at different sowing dates. In this paper, the whole process of rice tillering was decomposed into two aspects: tiller occurrence and tiller extinction, and two Logistic functions were used to describe them respectively, so as to establish a dynamic tillering model in rice based on double Logistic function (**Dynamic Tillering Model, DTM**). Then, according to **DTM**, dynamic tillering indexes (**DTIs**) were defined and their calculation formulas were derived. Finally, the characteristics and laws of rice tillering dynamic response to sowing dates were analyzed using **DTM** and **DTIs** with the observed tillering data of three rice varieties, (Hui-Liangyou 898 (HLY898), Y-Liangyou 900 (YLY900) and Y-Liangyou 911 (YLY911)), in six sowing dates (March 15, March 20, March 25, March 30, April 5, April 10). The results show that: 1. The model fits well. The normalized RMSE (RMSEn) of the **DTM** fitted to the observed tillering data of different rice varieties sown at different times were all less than 10 %, and their mean values were less than 5 %. 2.The variation degree of **DTIs** under the influence of sowing dates had certain consistency among the three rice varieties. the inherent rate of tillering ($\mathbf{R_{it}}$), the maximum tillering rate ($\mathbf{R_{mt}}$), the maximum tillers extinction rate ($\mathbf{R_{me}}$) and the duration of tillering ($\mathbf{D_t}$) varied greatly, while the total number of grow tillers ($\mathbf{N_g}$), the peak time of tillering ($\mathbf{T_{pt}}$), the peak time of tillers extinction ($\mathbf{T_{pe}}$) and the end time of tillering ($\mathbf{T_{et}}$) had smaller variation. 3. The eight **DTIs**, the inherent rate of tillering ($\mathbf{R_{it}}$), the duration of tillering ($\mathbf{D_t}$), the maximum tillering rate ($\mathbf{R_{mt}}$), the number of retained tillers ($\mathbf{N_r}$), the peak time of tillering ($\mathbf{T_{pt}}$), the end time of tillering ($\mathbf{T_{et}}$), the start time of tillers extinction ($\mathbf{T_{se}}$) and duration of tillers extinction ($\mathbf{D_e}$), had a consistent linear response to the sowing dates among the three rice varieties. 4. Under different sowing dates, the dynamic characteristics of tillering of YLY900 and YLY911 were relatively close, while HLY898 had great differences from YLY900 and YLY911. In this paper, the evolution process of the number of tillers of rice was accurately described by the **DTM**, and the regularity and characteristics of tillering dynamics of rice were deeply revealed using the **DTIs**, with agronomic experiment of three varieties with six sowing dates. Therefore, it has important theoretical value to deeply understand

* Corresponding author.
E-mail address: xm.li@hunau.edu.cn (X. Li).

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the law of the tillering dynamic of rice affected by sowing dates and has important practical significance for guiding accurate planting and fine management of rice production from the perspective of grasping tillering dynamics.

1. Introduction

Panicle number per unit area is a component factor of rice yield [1,2], and the tillering stage is a key stage to determine panicle number ([3,4]; Yu et al., 2011). Combining tillering characteristics and dynamic rules of rice varieties, appropriate cultivation measures to control tillering number are one of the important ways to increase effective panicle number per unit area and achieve high yield [5,6]. Tillering ability and tillering process of rice are affected by light and temperature conditions [7,8], and for a given region, sowing date is an optional light-temperature condition adjustment scheme during rice production. Therefore, it is of great significance to establish an accurate and explainable dynamic tillering model and study the dynamic tillering characteristics of rice at different sowing dates, which can guide the precise control of tillering process and realize the high and stable yield of rice.

Tillering dynamics are controlled by genotypes [9,10] and regulated by ecological environment [11,12]. Since the 1920s, rice tillering has been the focus of attention of rice breeders and cultivators. Research on tillering in rice can be divided into four aspects: First, research on controlling genes of tillering in rice focuses on locating controlling genes of tillering to assist molecular breeding [9]; Second, research on the regularity of tillering in rice and its influencing factors, focusing on the description of individual tillering characteristics and characteristics [13–15]; Third, research on the number of tillers in rice population focuses on seeking the relationship and equation between the growth and decline of tillers in rice population and time or habitat factors ([16]; [17,18]). Fourth, the simulation of tillering dynamics in rice population focuses on finding out the combination of factors that lead to the trajectory of the optimal tillering number and guiding the implementation of agronomic measures in rice production [19–21].

According to the selection of explanatory variables, the simulation model of tillering dynamics in rice population can be summarized into four categories: First, the mathematical model to calculate the theoretical tillering number of rice according to the age of main stem and leaf [13]; Second, the growth and decline model of tillers based on time ([19]; Wang et al., 1997); Third, the growth and decline model of stems and tillers based on effective accumulated temperature [20]; Fourth, a complex model was established based on several habitat factors as explanatory variables [7]. The dynamic change of tiller and stem in rice population is the result of various factors such as variety, sowing date, density, fertilizer, water, etc. The limitation of leaf age as explanatory variable is that leaf age itself is also affected by many habitat factors. There are various models for dynamic simulation of rice stalk and tiller, including single factor statistical model with time t as the independent variable, multi-factor statistical model integrating climate and cultivation factors, and process model with strong mechanism. Wang and Huang [22] believe that considering the universality of the model, it is most suitable to replace the comprehensive environmental stress with time as the independent variable.

Under conventional production conditions, the number of stems and tillers in rice population showed a unipeak trend with the number of days after greening after transplanting, which roughly experienced a process from the beginning of transplanting to the peak of tillering, and then a decrease until the change ended [23]. Therefore, the dynamics of stems and tillers in rice population were usually divided into two stages: growth and extinction. Based on the characteristics of stem and tiller growth of rice population, Wang and Huang [22] used Logistics function to describe the growth and extinction process, built a DMOR dynamic empirical model of rice stem and tiller, and classified different rice populations. Sun et al. [21] used Logistics and modified Logistics functions to describe the growth and extinction process, built an empirical model of FACE rice stalk and tiller dynamics to describe the growth and extinction process, and simulated the stalk and tiller dynamics under the condition of CO_2 concentration doubling. Yu (et al., 2019).studied the effects of irrigation and discharge mode and nitrogen application level on the growth dynamics of stems and tillers of rice based on DMOR empirical model.

With time as the variable, based on the characteristics of tillering and stem growth in rice population and combined with empirical data, a dynamic tillering number model was constructed to simulate and analyze the influences of variety, cultivation measures, ecological environment and other factors, so as to guide the precise cultivation of rice. The key problem lies in the simulation model with high precision, good interpretation and wide application. Sowing date adjustment is an important means to regulate light and temperature conditions in rice production, and light and temperature conditions have a significant impact on rice yield quality [24,25]. Planting crops at the optimal sowing date can make full use of local natural resources such as warm and light water and the growing season to ensure that crops are in the most suitable environment for growth and development from planting to harvest, which is conducive to high yield, stable yield and improved quality. Therefore, this paper will construct a double Logistic model to simulate the dynamic process of tillering number of rice population according to the change characteristics of tiller and stem with the sowing date, analyze the quantitative relationship between the dynamic characteristics of tillering in different rice varieties and the response of rice planting time, and reveal the law of the influence of sowing date on the dynamic tillering number of rice population.

2. Materials and methods

2.1. Construction of dynamic model of tiller number

Under conventional conditions, the number of tillers N in rice population showed a unimodal curve with time [23]. If the natural disaster, biological and human factors are not considered, the number of rice tillers maintained at the later stage is essentially the difference between the number of occurrence and the number of death of rice tillers. Therefore, the dynamic change process of tiller number is determined by two aspects, namely occurrence and death. After seedling emergence or regreening, the main factors affecting the number of tillers were the occurrence of tillers. With the increase of population number, the competition for habitat resources between stems and tillers intensified, especially the competition for light radiation, and the light duration and radiation intensity in the lower part of the population decreased sharply [22]. This results in two changes: first, the development of tillers slows down until they stop (or the tillering dies before reaching the scale that can be observed by the naked eye), and second, the weak tillers that have occurred within the population begin to die. Relative to the occurrence of tiller, the beginning time of tiller death was delayed. Since the occurrence and death of tillers are both affected by habitat resources, the changes in the number of occurrence and death of tillers conform to the "S" curve, which can be described by the classical population growth model –Logistic function [26,27].

Let N(t), NC(t) and ND(t) be the number of tillers, cumulative occurrence tillers and cumulative death tillers of rice population from transplanting to time *t*, respectively. Based on the above analysis, the following models can be obtained.

2.1.1. Tiller generation model

$$NG(t) = \frac{N_g}{1 + e^{-a_1(t-b_1)}} \tag{1}$$

N_g is the total number of growing tillers, which is generally greater than or equal to the observed maximum number of tillers; a_1 is the inherent rate of tillering (R_{is}) and b_1 is the peak time of tillering (T_{pt}), when the number of tillers that have occurred is half of the total number of tillers that have occurred.

2.2. Tiller extinction model

$$NE(t) = \frac{N_e}{1 + e^{-a_2(t-b_2)}} \tag{2}$$

Where, N_e is the total number of extincted tillers, which is less than the actual maximum number of tillers; a_2 is the inherent rate of tillers extinction (**R_{ie}**); b_2 is the peak time of tillers extinction (**T_{pe}**), when the number of extincted tillers is half of the total number of extincted tillers. Under normal conditions, the time when the tiller dies the fastest lags behind the time when the tiller increases the most, that is, $b_2 > b1$.

2.2.1. Dynamic tillering model

The whole process of rice tillering was decomposed into two aspects: tiller occurrence and tiller extinction, then, the dynamic tillering model (**DTM**) could be established through integrating the tiller occurrence model and the tiller extinction model, whose form is as follows.

$$N(t) = NG(t) - NE(t) = \frac{N_g}{1 + e^{-a_1(t-b_1)}} - \frac{N_e}{1 + e^{-a_2(t-b_2)}} \tag{3}$$

2.3. Calculation of tillering dynamic index

The tillering process of rice after transplanting is roughly as follows (Fig. 1) [23].: (1) Tillering starts after greening, that is, the start time of tillering (**T_{st}**); (2) Tillering acceleration reaches the fastest, that is, the peak time of tillers extinction (**T_{pe}**); (3) Tiller deceleration until stop tillering, that is, the end time of tillering (**T_{et}**), during which tillering begins to die, that is, the start time of tillers extinction (**T_{se}**); (4) Tillering acceleration reaches the fastest, that is, the peak time of tillers extinction (**T_{pe}**); (5) The tillering deceleration until the tillering stop, that is, the end time of tillers extinction (**T_{ee}**) (6) Since then, the number of tillers has remained basically unchanged. The dynamic tillering indexes (**DTIs)** were defined based on the analysis of tiller dynamic characteristics, the properties of Logistic model and the biological significance of its parameters.

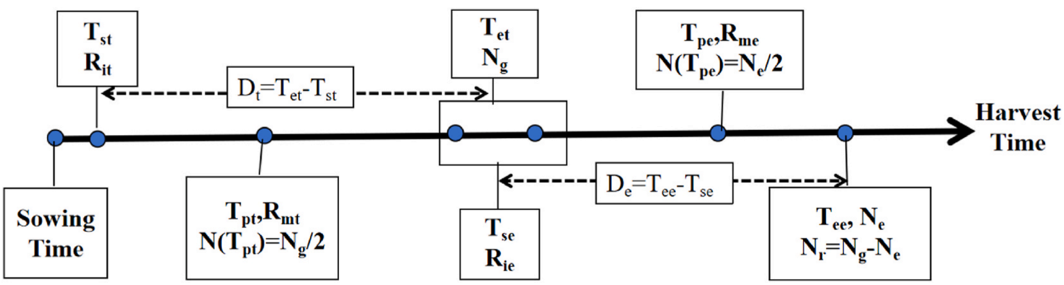


Fig. 1. Dynamic process and characteristic index of rice tillering.

The total number of growing tillers (N_g) is the total number of tillers after tillering is completed.

The start time of tillering (**T_{st}**) is the moment when tillering begins to occur, when the number of tillers occurring is 0. NG(t) is monotone and $\lim_{t\to-\infty} NG(t) = 0$, For this reason, **$T_{st}$** is defined as the time when the cumulative number of tillers reaches $(1-p)\cdot N_g$, $NG(T_{st}) = (1-p)\cdot Ns$, and where p is a value close to 1, taking the value 95 %. Without special explanation, p in the following article is the same.

The peak time of tillering (**T_{pt}**) is the moment when the rate of tillering is the highest. According to the Logistic model properties, $NG(T_{pt}) = N_g/2, T_{pt} = b_1$.

The maximum tillering rate (**R_{mt}**) is the maximum rate of tillering. It is known by the properties of the Logistic model, when $NG(t) = N_g/2$, the rate of tillering is the highest, $R_{mt} = \frac{dNG(t)}{dt}\Big|_{NG(t)=\frac{N_g}{2}} = \frac{a_1 N_g}{4}$。

The end time of tillering (**T_{et}**) is the moment when tillering ends. Similar to **T_{st}**, **T_{et}** is defined as the time for the cumulative number of tillers to reach $p\cdot Ng$.

The duration of tillering (**D_t**) is the total duration experienced from **T_{st}** at the beginning of tillering to **T_{et}** at the end of tillering, $D_t =$ **T_{et}** -T_{ss}, $D_t = -\frac{2}{a_1} ln\left(\frac{1-p}{p}\right)$.

The total number of extincted tillers (**N_e**) is the total number of tillers that die.

The start time of tillers extinction (**T_{se}**) is the moment when tillering begins to die. Similar to **T_{st}**, $T_{se} = b_2 + \frac{1}{a_2} ln\left(\frac{1-p}{p}\right)$.

the peak time of tillers extinction (**T_{pe}**) is the moment when tiller extinction rate is maximum. From the Logistic model properties, $Ne(T_{pe}) = N_e/2$, $T_{pe} = b_2$.

The maximum tillers extinction rate (**R_{me}**) is the maximum rate of tillers extinction. It is known by the properties of the Logistic model, when $NE(t) = N_d/2$, $R_{me} = \frac{dNE(t)}{dt}\Big|_{NE(t)=\frac{N_e}{2}} = \frac{a_2 N_e}{4}$.

The end time of tillers extinction (**T_{ee}**) is the moment when tillers extinction ends. Similar to **T_{et}**, $T_{ee} = b_2 - \frac{1}{a_2} ln\left(\frac{1-p}{p}\right)$.

The duration of tillers extinction (**D_e**) is the total duration from **T_{se}** at the beginning of tillers extinction to **T_{ee}** at the end of tillers extinction, **$D_e = T_{ee} - T_{se}$**, $D_e = -\frac{2}{a_2} ln\left(\frac{1-p}{p}\right)$,

the total number of retained tillers (**N_r**) is increased tillering number of rice population at harvest, that equals to the difference between the total number of tillering and the total number of extincted tillers, that is $N_r = N_g - N_e$.

2.4. Data Sources

The data were derived from the rice cultivation comparative experiments of different plant types and different planting times conducted by the research group in 2019 and 2022. The experiment was conducted at Shunyong Rice Planting Cooperative in Changsha County, Changsha City, Hunan Province (N latitude N28°03 ′59.17 ″, E longitude E113°11′ 52.47 ″). Three rice varieties, HLY898, YLY900 and YLY911, were used as experimental materials, and six different planting periods were set up. The planting dates were: March 15, March 20, March 25, March 30, April 5, April 10, and four leaves in one heart were transplanted. The experiment consisted of 18 treatments with 3 replicates per treatment. 54 plots were arranged in the same hill paddy field using a completely randomized block design. The transplanting density is 20cm × 20 cm, and other conditions such as water and fertilizer management are exactly the same. Ten points of rice were identified in each plot as the observation object of tillering number. From 15 days to 80 days after transplanting, the number of tillers was observed every 5 days, a total of 15 times. In this paper, the observed data of the number of tillers were used to test the model, and the law of the influence of sowing dates on the dynamic number of tillers was analyzed.

2.5. Parameter calculation

The DTM (Formula 3) is a nonlinear model whose parameters are determined by the least square method and calculated by the Levenberg-Marquardt algorithm of software Matlab R2016a [28–30]. According to the biological significance of the parameters, the range of six parameters is defined as: max(observed number of tillers) < **N_g** < 1.2 × max(observation tillers number); 0 < **a_1** < +∞; 0 < **b_1** < +∞; 0 < **N_e** < 1.2 × max(observation tillers number)- the number of tillers last observed; 0 < **a_2** < +∞; 15 < **b_2** < 65。

2.6. Methods of model testing

The normalized RMSE (RMSEn, see Formula 4) and R^2 value are used to test the simulation effect of the model. An RMSEn value of less than 10 % indicates the simulation effect is excellent; between 10 % and 20 % indicates very good; indicates 20 % and 30 % indicates good; RMSEn value of greater than 30 % indicates the simulation effect is poor, in that case, the simulation value deviates greatly from the actual value [11,31,32].

$$\mathrm{RMSEn} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{OBS_i} - \mathrm{SIM_i})^2}{n}} \times \frac{1}{\overline{\mathrm{OBS}}} \times 100\% \tag{4}$$

3. Results

3.1. Goodness-of-fit test for DTM

Goodness of fit is an important index to evaluate how well a model fits data, and it is extremely necessary. The dynamic tillering model fitted the dynamic tillering data observed in the experiment (Fig. 2), and the RMSEn and R^2 of the model fitting were calculated. The result shows that the RMSEn was between 3 % and 7 %, and the mean value of the two years was less than 5 %. and all fitted R^2 is greater than 0.99. Therefore, the DTM has excellent Goodness of fit for all test.

3.2. Variation analysis of DTIs at different sowing dates

To explain how much the sowing date affects the **DTIs,** the variation range, coefficient of variation and variation ranking of the **DTIs** of three rice varieties of HLY898, YLY900 and YLY911 in the two-year sowing experiments conducted in 2019 and 2022 are calculated, as Table 1. Further analysis showed that there was a certain consistency in the variation order of tillering dynamic indicators among the three rice varieties. The variation of the inherent rate of tillering $\mathbf{R_{it}}$, the duration of tillering $\mathbf{D_t}$, the maximum tillering rate $\mathbf{R_{mt}}$ and the maximum tillers extinction rate $\mathbf{R_{me}}$ ranked the top six. The total number of growing tillers $\mathbf{N_g}$, the peak time of tillering $\mathbf{T_{pt}}$, the peak time of tillers extinction $\mathbf{T_{pe}}$, and the end time of tillers extinction $\mathbf{T_{ee}}$ ranked in the bottom five. The variation of the inherent rate of tillers extinction $\mathbf{R_{ie}}$, the end time of tillering $\mathbf{T_{et}}$ and the duration of tillers extinction $\mathbf{D_e}$ were all in the middle five. the total number of extincted tillers $\mathbf{N_e}$, the total number of retained tillers $\mathbf{N_r}$ and the start time of tillering $\mathbf{T_{st}}$ were different among the three varieties.

3.3. Regression analysis of DTIs in response to sowing date

The adjustment of sowing date is an important agronomic measure to regulate the number of tillers. Taking sowing dates as the independent variable, the law of tiller dynamic response to sowing dates was analyzed based on linear regression, and R^2 was shown in Table 2. The table shows that the inherent rate of tillers extinction $\mathbf{R_{it}}$, the peak time of tillering $\mathbf{T_{pt}}$, the total number of retained tillers $\mathbf{N_r}$, the end time of tillering T_{et}, the duration of tillering D_t, the duration of tillers extinction $\mathbf{D_e}$ and the maximum tillering rate $\mathbf{R_{mt}}$ of three rice varieties HLY 898, YLY900 and YLY911 have a consistent linear response law to planting time.

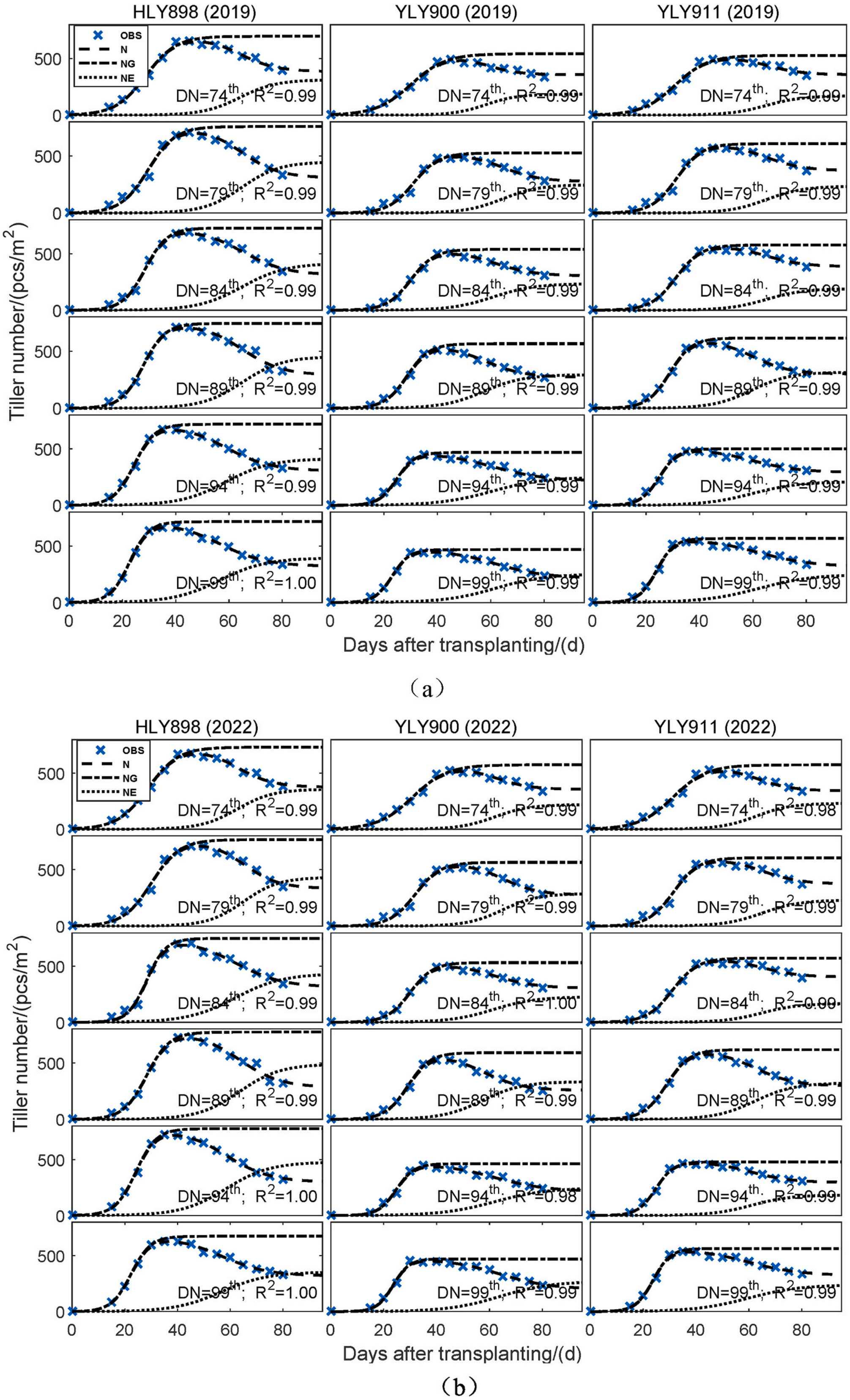
The trend analysis showed that with the delay of seeding time, the inherent rate of tillering $\mathbf{R_{it}}$, and the maximum tillering rate $\mathbf{R_{mt}}$ increased, the total number of retained tillers $\mathbf{N_r}$ decreased, the peak time of tillering $\mathbf{T_{pt}}$ came early, the end time of tillering T_{et} pushed back, the duration of tillering $\mathbf{D_t}$ shortened, the start time of tillers extinction $\mathbf{T_{se}}$ come early, and the duration of tillers extinction $\mathbf{D_e}$ prolonged.

The quantitative analysis showed when sowing date is delayed by one week, the inherent rate of tillering $\mathbf{R_{it}}$ of **HLY898** increases by 0.025 pcs/m^2/d, the maximum tillering rate $\mathbf{R_{mt}}$ increases 4.3 pcs/m^2/d, and the total number of retained tillers $\mathbf{N_r}$ reduces 15.4 pcs/m^2, the peak time of tillering $\mathbf{T_{pt}}$ comes earlier 1.9d, the end time of tillering $\mathbf{T_{et}}$ comes earlier 3.5d, the duration of tillering $\mathbf{D_t}$ shortens 3.2d, the start time of tillers extinction $\mathbf{T_{se}}$ comes earlier 3.6d, and the duration of tillers extinction $\mathbf{D_e}$ prolongs 3.1d; the inherent rate of tillering $\mathbf{R_{it}}$ of **YLY900** increases 0.038 pcs/m^2/d, the inherent rate of tillering $\mathbf{R_{mt}}$ increases 3.9 pcs/m^2/d, and the total number of retained tillers $\mathbf{N_r}$ decreases 38.2 pcs/m^2, the peak time of tillering $\mathbf{T_{pt}}$ comes earlier 2.3d, the end time of tillering $\mathbf{T_{et}}$ comes earlier 4.7d, the duration of tillering $\mathbf{D_t}$ shortens 5.0d, the start time of tillers extinction $\mathbf{T_{se}}$ comes earlier 3.0d, the duration of tillers extinction $\mathbf{D_e}$ prolongs 5.8d; the inherent rate of tillering $\mathbf{R_{it}}$ of **YLY911** increases 0.038 pcs/m^2/d, the inherent rate of tillering $\mathbf{R_{mt}}$ increases 4.8 pcs/m^2/d, and the total number of retained tillers $\mathbf{N_r}$ decreases 15.9 pcs/m^2, the peak time of tillering $\mathbf{T_{pt}}$ comes earlier 2.4d, the end time of tillering $\mathbf{T_{et}}$ comes earlier by 4.5d, the duration of tillering $\mathbf{D_t}$ shortens 4.5d, the start time of tillers extinction $\mathbf{T_{se}}$ comes earlier 3.0d, and the duration of tillers extinction $\mathbf{D_e}$ prolongs 3.6d.

3.4. Comparative analysis of DTIs on varieties

The correlation coefficients of tillering dynamic indexes between varieties at different sowed dates were calculated, and the paired sample *t*-test was used to compare and analyze the tillering dynamic characteristics among varieties. The results are shown in Table 3.

There were significant differences between HLY898 and YLY900 in 5 terms of **DTIs**:the peak time of tillering $\mathbf{T_{pt}}$, the end time of tillering Tet, the duration of tillering $\mathbf{D_t}$, the start time of tillers extinction $\mathbf{T_{se}}$, the duration of tillers extinction $\mathbf{D_e}$; there were significant differences between HLY898 and YLY900 in 7 **DTIs**, including the total number of growing tillers $\mathbf{N_g}$, the total number of extincted tillers $\mathbf{N_e}$, the total number of retained tillers $\mathbf{N_r}$, the start time of tillering $\mathbf{T_{st}}$, the peak time of tillering $\mathbf{T_{pt}}$, the maximum tillering rate $\mathbf{R_{mt}}$, the maximum tillers extinction rate $\mathbf{R_{me}}$. (2) There were significant correlations between HLY898 and YLY911 in 4 terms of **DTIs**, including The start time of tillering $\mathbf{T_{st}}$, the peak time of tillering $\mathbf{T_{pt}}$, the peak time of tillers extinction $\mathbf{T_{pe}}$, the end time of tillering $\mathbf{T_{et}}$. There were significant differences between HLY898 and YLY911 in six terms **DTIs**, including the total number of growing tillers $\mathbf{N_g}$, the total number of extincted tillers $\mathbf{N_e}$, The start time of tillering $\mathbf{T_{st}}$, the peak time of tillering $\mathbf{T_{pt}}$, the maximum tillering rate $\mathbf{R_{mt}}$, the maximum tillers extinction rate $\mathbf{R_{me}}$. (3) There were significant correlations between YLY900 and YLY911 in 9



(caption on next page)

Fig. 2. Simulation of dynamics tillering for sowing-day experiments.OBS: the observed tiller number; N: the number of tilles; NG: the number of growing tillers; NE: the number of extincted tillers.

Table 1
Variation analysis of DTIs on sowing dates (March 15, March 20, March 25, March 30, April 5, April 10 in 2019 and 2022).

	HLY898			YLY900			YLY911		
	RV	CV	CV_Order	RV	CV	CV_Order	RV	CV	CV_Order
N_g	(673.5775.6)	3.72	14	(462.2775.6)	8.25	13	(478.8615.9)	7.50	13
R_{it}	(0.17,0.28)	15.93	2	(0.15,0.28)	22.37	2	(0.16,0.3)	20.93	4
T_{pt}	(22.4,30.1)	9.75	11	(23.5,31.0)	10.85	12	(23.7,31.5)	10.86	12
N_e	(354.0,489.0)	11.97	7	(219.0,489.0)	13.91	10	(168.0,321.0)	21.03	3
R_{ie}	(0.11,0.15)	10.42	9	(0.1,0.15)	16.45	7	(0.1,0.15)	12.70	9
T_{pe}	(56.7,65.0)	5.08	13	(57.4,65.0)	3.84	15	(59.7,65.0)	3.44	14
N_r	(283,375.3)	9.31	12	(201.3355.6)	18.64	4	(294.9405)	11.31	10
T_{st}	(11.4,17.7)	13.86	5	(11.8,17.7)	13.94	9	(12.5,17.4)	11.31	11
T_{et}	(33.4,45.9)	11.27	8	(32.6,50.2)	14.34	8	(33.5,50.2)	13.80	7
D_t	(21.3,34.0)	17.27	1	(18.0,38.4)	24.79	1	(19.5,37.7)	22.14	2
T_{se}	(30.7,45.2)	13.21	6	(33.1,45.2)	11.28	11	(30.6,44.2)	12.35	8
T_{ee}	(82.6,88.4)	2.64	15	(79.5,88.4)	5.68	14	(82.3,88.8)	3.21	15
D_e	(39.6,53.1)	10.14	10	(38.3,53.1)	16.58	5	(39.2,58.2)	14.81	6
R_{mt}	(31.7,51.8)	15.66	3	(22.1,51.8)	16.46	6	(22.4,42.6)	19.07	5
R_{me}	(10.0,16.0)	14.29	4	(6.3,16.0)	18.76	3	(6.0,10.8)	23.74	1

Note:RV is Range of variation (i.e. (minimum, maximum)), CV is Coefficient of variation (i.e. standard deviation/average × 100 %), and CV_Order is Order of CV values (descending order).

Table 2
Regression equation of tillering dynamic response to sowing dates.

	Regression equations					
	2019 Year			2022 Year		
	HLY898	YLY900	YLY911	HLY898	YLY900	YLY911
R_{it}	0.003x-0.096	0.006x-0.281	0.006x-0.244	0.004x-0.096	0.005x-0.162	0.005x-0.162
T_{pt}	−0.268x+50.129	−0.318x+55.459	−0.323x+56.48	−0.284x+51.615	−0.3428x+58.057	−0.347x+58.586
N_r	−2.038x+496.73	−5.225x+726.04	−2.038x+496.73	−2.379x+526.55	−5.726x+763.91	−2.518x+557.22
T_{et}	−0.500x+83.37	−0.660x+98.083	−0.630x+96.023	−0.516x+84.817	−0.701x+102.03	−0.682x+100.78
D_t	−0.465x+66.491	−0.685x+85.268	−0.614x+79.109	−0.463x+66.37	−0.725x+88.608	−0.675x+84.858
T_{se}	−0.531x+85.28	−0.408x+72.698	−0.577x+89.652	−0.504x+81.629	−0.434x+75.832	−0.461x+80.172
D_e	0.427x+9.137	0.851x-27.126	0.7568x-19.32	0.462x+6.695	0.829x-24.304	0.589x-6.177
R_{mt}	0.682x-17.294	0.560x-17.896	0.702x-27.361	0.567x-6.692	0.567x-17.466	0.671x-25.162
	R^2					
R_{it}	0.92	0.96	0.95	0.47	0.69	0.69
T_{pt}	0.82	0.83	0.83	0.79	0.86	0.87
N_r	0.71	0.84	0.83	0.00	0.43	0.43
T_{et}	0.63	0.84	0.51	0.48	0.87	0.69
D_t	0.97	0.97	0.95	0.88	0.97	0.95
T_{se}	0.89	0.86	0.91	0.66	0.89	0.89
D_e	0.80	0.71	0.91	0.71	0.72	0.71
R_{mt}	0.78	0.86	0.79	0.55	0.84	0.66

terms of **DTIs**, the total number of growing tillers $\mathbf{N_g}$, the total number of extincted tillers $\mathbf{N_e}$, the inherent rate of tillering $\mathbf{R_{it}}$, the inherent rate of tillers extinction $\mathbf{R_{ie}}$, the start time of tillering $\mathbf{T_{st}}$, the peak time of tillering $\mathbf{T_{pt}}$, the end time of tillering $\mathbf{T_{et}}$, the maximum tillering rate $\mathbf{R_{mt}}$, the maximum tillers extinction rate $\mathbf{R_{me}}$. There were significant differences between HLY898 and YLY911 in the three terms of **DTIs**: the total number of growing tillers $\mathbf{N_g}$, the total number of retained tillers N_r.

4. Discussion

4.1. Comparison of dynamic tillering models

Predecessor used Logistics function to describe the growing and extinction process, constructed DMOR rice tillering dynamic empirical model, and studied the effect of variety, CO_2 concentration and irrigation on rice population tillering ([19]; Wang et al., 1997). Compared with the previous tiller dynamic models, DMOR model has obvious advantages in concise model assumption, simple model form, clear parameter meaning and fitting effect. The **DTM** model (Formula 3) in this paper improves the structural form of the

Table 3
Correlation and comparative analysis of different varieties on **DTIs**.

	Correlation			Difference		
	HLY898 v.s. YLY900	HLY898 v.s. YLY911	YLY900 v.s. YLY911	HLY898 v.s. YLY900	HLY898 v.s. YLY911	YLY911 v.s. YLY900
$\mathbf{N_g}$	0.37	−0.04	**0.82****	**212.15****	**176.35****	**35.80****
$\mathbf{R_{it}}$	0.71	0.71	**1.00****	0.02	0.02	0
$\mathbf{T_{pt}}$	**0.99****	**0.97****	**0.99****	**−1.40****	**−1.53****	0.13
$\mathbf{N_e}$	0.48	0.13	**0.82****	**160.00****	**195.00****	**−35.00****
$\mathbf{R_{ie}}$	0	0	**1.00****	−0.02	−0.02	0
$\mathbf{T_{pe}}$	−0.2	**0.81****	0.08	−0.6	−1.27	0.67
$\mathbf{N_r}$	0.69	0.41	0.55	**52.15****	−18.65	**70.80****
$\mathbf{T_{st}}$	0.75	**0.80****	**0.99****	**−1.58***	**−1.42***	−0.17
$\mathbf{T_{et}}$	**0.95****	**0.90****	**0.99****	−1.2	−1.63	0.43
$\mathbf{D_t}$	**0.85****	0.78	**0.99****	0.45	−0.2	0.65
$\mathbf{T_{se}}$	**0.80****	0.72	0.56	−0.28	−2.25	1.97
$\mathbf{T_{ee}}$	−0.44	0.08	0.51	−1	−0.37	−0.63
$\mathbf{D_e}$	**0.81****	0.53	0.67	−0.73	1.9	−2.63
$\mathbf{R_{mt}}$	0.67	0.54	**0.98****	**11.37****	**10.07****	1.3
$\mathbf{R_{me}}$	0.74	0.65	**0.87****	**5.08****	**5.88****	−0.8

DMOR model, and whose parameters is clearer. For example, in the DMOR model, C_1, b_1, C_2 and b_2 are only defined as control parameters, and their biological meaning is not clearly given. In **DTM** model, $\mathbf{a_1}$ is the inherent rate of tillering $\mathbf{R_{it}}$, $\mathbf{b_1}$ is the peak time of tillering $\mathbf{T_{pt}}$ (when the number of tillers reaches half of the maximum number of tillers), $\mathbf{a_2}$ is the inherent rate of tillers extinction $\mathbf{R_{ie}}$, $\mathbf{b_2}$ is the time of maximum growth of tillers $\mathbf{T_{pe}}$ (when the number of tillers reaches half of the maximum number of tillers), whose biological significance is clearer. As a result, The **DTM** model in this paper has better solvability, easier initial value setting, and faster convergence speed. Due to the nonlinearity of least squares fitting, the solution iteration often falls into the local optimal solution [32–34]. Numerical experiments show that the solution of the DMOR model is very sensitive to the initial value setting, and it is difficult to obtain the global optimal solution. Setting the range of the six parameters of **DTM** according to the biological significance as Section 2.4, the optimal solution of a **DTM** model could be obtained within 20 ms with the Levenberg-Marquardt algorithm of Matlab R2016a running on the computer with the configuration: CPUIntel (R) Core (TM) i5-4200U CPU @ 1.6 GHz and memory 4 GB.

In addition, 15 DTIs were defined based on the DTM model, including three important indicators of the number of tillers ($\mathbf{N_g}$, $\mathbf{N_e}$, $\mathbf{N_r}$), four important indicators of the change rate of tillers ($\mathbf{R_{it}}$,$\mathbf{R_{mt}}$, $\mathbf{R_{ie}}$, $\mathbf{R_{me}}$), and six important time node indicators ($\mathbf{T_{st}}$, $\mathbf{T_{pt}}$, $\mathbf{T_{et}}$, $\mathbf{T_{se}}$, $\mathbf{T_{pe}}$, $\mathbf{T_{ee}}$), and two duration indicators ($\mathbf{D_t}$, $\mathbf{D_e}$). A total of 15 indexes in 4 groups quantified the whole process of tillering dynamic changes, which provided comprehensive quantitative indexes for the comparison of tillering dynamics in different treatments. However, the data dependent on the model in this paper needs manual measurement, and the efficiency of data acquisition is low. How to integrate the high-throughput information obtained by UAV aerial photography and other methods to improve the dynamic tillering model is still worth exploring.

4.2. Regularity of tillering dynamics on sowing dates

Sowing date affected the development rate of rice, changed the length of each growth stage, and then affected the accumulation of photosynthetic substances and the formation of yield. In addition to genetic factors, the growth period of rice is also affected by ecological climate, among which temperature is the most significant influence. With the delay of sowing date, the growth process of rice was delayed correspondingly, and the yield and effective panicle number showed a decreasing trend [24].

The results in this study (Table 2) showed that the tillering stage Dt of HLY898, YLY900 and YLY90 was shortened by 3.2 days, 5.0 days and 4.5 days respectively, which was consistent with the previous research conclusions [24,25]. The reasons for the shortened $\mathbf{D_t}$ are as follows: when the sowing date is delayed, the daily average temperature increases, and then the tillering rate accelerates under the influence of high temperature, that is, the intrinsic tillering rate $\mathbf{R_{it}}$ and the maximum tillering efficiency $\mathbf{R_{mt}}$ increase, which leads to the advance of the peak time $\mathbf{T_{pt}}$ and the end time $\mathbf{T_{et}}$ of tillering, and the shortening of the time $\mathbf{D_t}$ of tillering.

Further analysis revealed that as the sowing date was delayed, the growth process of rice was delayed, the tillering $\mathbf{D_t}$ time was shortened, and rice entered reproductive growth earlier from vegetative growth, which led to the death of more tillers due to lack of nutrients. As a result, when the sowing date was postponed for one week, the total number of retained tillers $\mathbf{N_r}$ of HLY898, YLY900 and YLY900 decreased by 15.4, 38.2 and 15.9 pcs/m^2 respectively, which was consistent with the previous research results [35]. In addition, the results of this study also showed that the duration of tillers extinction $\mathbf{D_e}$ was prolonged with the delay of sowing date, which may be due to the increase of population photo-products [36].

However, when the application is extended to a wider range, due to different habitat factors, the quantitative conclusions of this model may face new challenges. In particular, the model needs to be further improved to make the law of tillering dynamic characteristics adapt to the wider latitude regions with different annual distribution of solar energy and thermal energy resources.

4.3. Characteristics of tillering dynamics on varieties

Tillering dynamics is controlled by gene types [11,37]. Previous studies suggest rice tillering is mainly formed by the differentiation and development of the axillary bud primordia at the base of the stem, and is mainly controlled by two types of genes: tillering initiation regulatory genes and tillering elongation genes [38], which are significant differences in genes among different rice varieties.

The three tested varieties HLY898, YLY900 and YLY911 used in this study are bred by 1892S × YR0822, Y58S × R900 and Y58S × Chuanghui 911, respectively. The results of this study (Table 3) showed that the dynamic tillering characteristics of YLY900 and YLY911 response to sowing dates were highly similar, as there 10 of the 15 **DTIs** were significantly correlated, while the correlation between YLY900, YLY911 and HLY898 was relatively lower. The reason may be that YLY900 and YLY911 have the same maternal origin, while HLY898 has different parental origin from YLY900 and YLY911. However, whether this conclusion is universal needs further verification, and the mechanism of its gene regulation needs further explored. Moreover, There were significant differences between HLY898 and YLY900, and between HLY898 and YLY911 in six dynamic tillering indicators, including the total number of growing tillers $\mathbf{N_g}$, the total number of extincted tillers $\mathbf{N_e}$, the start time of tillering $\mathbf{T_{st}}$, the peak time of tillering $\mathbf{T_{pt}}$, the maximum tillering rate $\mathbf{R_{mt}}$ and the maximum tillers extinction rate $\mathbf{R_{me}}$. The total number of growing tillers $\mathbf{N_g}$ and the total number of extincted tillers $\mathbf{N_e}$ of HLY898 were significantly higher than both of YLY900 and YLY911, which was consistent with the fact that the maximum tillering rate $\mathbf{R_{mt}}$ and the maximum tillers extinction rate $\mathbf{R_{me}}$ of HLY898 were significantly higher than those of YLY900 and YLY911. However, the total number of retained tillers $\mathbf{N_r}$ of HLY898 and YLY911 was significantly higher than that of YLY900, and YLY911 was slightly higher than that of HLY898. From the analysis of the relationship between the characteristics of tillering process, that because HLY898 had both the highest total number of growing tillers $\mathbf{N_g}$ and total number of extincted tillers $\mathbf{N_e}$, while YLY911 had the higher number of growing tillers $\mathbf{N_g}$ and the lowest total number of extincted tillers $\mathbf{N_e}$, and YLY900 has the lower number of growing tillers $\mathbf{N_g}$ and higher total number of extincted tillers $\mathbf{N_e}$. the total number of retained tillers N_r was consistent with the panicle type of the three varieties: YLY900 belonged to fewer panicle and more grain type, while HLY 898 and YLY911 belonged to moderate panicle and grain type[39]. However, the relationship between the number of growing tillers $\mathbf{N_g}$, the total number of extincted tillers $\mathbf{N_e}$ and stem and leaf morphology of different varieties and the morphology of stems and leaves as well as their regulatory genes still need to be further explored [40,41].

5. Conclusion

Establishing dynamic tillering model for different types of rice and simulating the effect of sowing date on dynamic tillering index of rice population is of great significance for achieving high and stable yield by adjusting sowing date. In this study, the improved tillering dynamic model has the advantages of concise assumptions, simple expressions, good interpretability, good goodness-of-fit and good solvability, and the extracted dynamic tillering indexes can be used for quantitative analysis of rice tiller dynamic characteristics in the whole process. Based on the dynamic tillering model and dynamic tillering indexes, this paper explored the effect of sowing date on tillering dynamics. The sowing date had the greatest impact on inherent tillering rate, maximum tillering rate, maximum tillering extinction rate and tillering duration. And when the sowing date was postponed, the increase of daily average temperature accelerated the tillering rate, advanced the peak time and the end time of tillering, shortened the tillering duration, and advanced the start time of tillers extinction, prolonged the tillering duration, and reduced the number of retained tillers. Moreover, among the three varieties tested (HLY898, YLY900 and YLY911 and), rice varieties YLY900 and YLY 911 with the same maternal parent had more similar trends in dynamic tillering characteristics in response to sowing dates.

CRediT authorship contribution statement

Xiaohui Wang: Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing. **Dang Zou:** Data curation, Investigation. **Can Li:** Data curation, Validation, Validation, Wei ZHOU, Data curation, Investigation. **Kefu Li:** Software. **Qiyuan Tang:** Conceptualization. **Xinghui Zhu:** Software. **Xumeng Li:** Conceptualization, Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. **Leping Cao:** Conceptualization, Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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