A Rice Model System for Determining Suitable Sowing and Transplanting Dates

Yueting Wu, Xiaolei Qiu, Ke Zhang, Zhiliang Chen, Alexis Pang, Yongchao Tian, Weixing Cao, Xiaojun Liu, and Yan Zhu

1 National Engineering and Technology Center for Information Agriculture, Nanjing Agricultural University, Nanjing 210095, China; 2017101053@njau.edu.cn (Y.W.); qiuxiaolei@njau.edu.cn (X.Q.); 2017201080@njau.edu.cn (K.Z.); chenzhiliang@njau.edu.cn (Z.C.); yctian@njau.edu.cn (Y.T.); caow@njau.edu.cn (W.C.)
2 MOE Engineering and Research Center for Smart Agriculture, Nanjing Agricultural University, Nanjing 210095, China
3 Key Laboratory for Crop System Analysis and Decision Making, Ministry of Agriculture and Rural Affairs, Nanjing Agricultural University, Nanjing 210095, China
4 Jiangsu Key Laboratory for Information Agriculture, Nanjing Agricultural University, Nanjing 210095, China
5 Jiangsu Collaborative Innovation Center for Modern Crop Production, Nanjing Agricultural University, Nanjing 210095, China
6 School of Agriculture and Food, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Building 184, Royal Parade, Parkville, Victoria 3010, Australia; alexis.pang@unimelb.edu.au
* Correspondence: liuxj@njau.edu.cn (X.L.); yanzhu@njau.edu.cn (Y.Z.)
† The first two authors contributed equally to this work.

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Abstract: Sowing and transplanting dates are important cultivation factors for rice production. Therefore, the present study focused on developing a rice model system that would be able to determine sowing and transplanting dates for diverse cultivars and planting methods in different agro-ecological zones. Different model parameters were integrated into a rice model system on the basis of their interaction effects in this study. The results showed that sowing and transplanting dates designed by the rice model system were approached to the planting dates recommended by local agricultural experts for high yield practices, with root mean squared error (RMSE) of 5.3 to 14.74 days. The model system accurately simulated suitable sowing and transplanting dates under most scenarios with relatively low RMSE, high linear correlation coefficient ($R^2$), and model efficiency (EF). Using the model system recommendations, rice yield under manual transplanting in low fertility soil was increased the most (5.5%), while for direct sowing in high fertility soil, yield increase was modest (0.8%). The newly-developed rice model system can act as a technical approach to design suitable sowing and transplanting dates for achieving high yield and effective crop production.

Keywords: rice; sowing date; transplanting date; model system; design

1. Introduction

Rice (Oryza sativa L.) is an important staple food crop, which feeds more than half of the world’s population [1]. It has been estimated that rice yields need to be increased by about 70% by 2050 to meet the rising global demand for direct human consumption [2]. For a sustainable agro-ecosystem and socio-economic development, it is imperative to maximize the use of existing arable land to increase rice yield while using material and human inputs efficiently [3]. One key strategy to improve grain yield is to adopt innovative cultivation techniques and integrate them into existing growing
systems. Innovations in agronomic practices play an important role in increasing yields and adapting cropping systems to climate change [4]. For example, farmers in northeast China have adjusted rice sowing and harvest timing on the basis of increasing trends in air temperature since the 1990s, resulting in increasing trends in rice yield of 16.6 kg ha\(^{-1}\) year\(^{-1}\) [5]. Currently, management technology innovations are the most effective technical means to increase grain yield in rice while minimizing additional material and human inputs [2].

Crop models are effective crop management technologies that can be used to simulate and evaluate the effects of different crop management practices [6,7]. Li et al. [8] demonstrated that ORYZA is a validated and calibrated crop model system that extrapolates the result of field experiments and accurately examines the effects of crop management practices. The crop model system, namely, the crop environment resource synthesis-rice (CSM-CERES-Rice) model can simulate fertilizer application, plant density, and irrigation in rice [9]. Agricultural Production Systems Simulator (APSIM) is a crop model system that performs well in simulating grain yield and analyzing farmer management practices under different seasons [10]. Though these crop model systems have numerous merits, there are some deficiencies limiting their application [11]. In particular, few of these models have the ability to determine optimal sowing and transplanting dates of rice under a wide range of different planting methods, cultivars and agro-ecological environments.

Sowing and transplanting dates have significant effects on rice growth, yield and quality [12–14]. Sowing and transplanting dates of rice are currently susceptible to climate warming [15,16]. Previous studies have suggested that an effective and simple way to mitigate the effects of global warming is to adjust sowing dates [17–20], although the decision on when to actually sowing is complex and fraught with uncertainty. Heat stress during reproductive stage shortens grain filling duration, lowers grain weight, and can lead to sterility in rice [17–21]. Krishnan et al. [22] demonstrated that sowing rice at optimal planting date was key to ensuring optimal temperatures during reproductive stage. Sowing and transplanting dates can be predicted by growing degree days (GDD) in crop models [15,23,24]. Growing degree days (GDD) of rice can be calculated by temperature and growing periods [25]. The rice growing period is affected by planting method, seedling age [26], cultivar and agroecological environment [27,28]. Zhang et al. [29] indicated that rice growth period shortened by 4.9 and 10.3 days under seedling throwing and mechanical transplanting, respectively, compared to manual transplanting. To address this research gap, these factors should be taken into account to develop a new rice model system for determining suitable sowing and transplanting dates during the modeling process.

The objectives of this study were to: (a) summarize factors influencing sowing and planting dates of rice, (b) develop a model to determine suitable sowing and transplanting dates under different planting methods, cultivars, and agro-ecological environments, and (c) validate the model system by evaluating the yield response to the simulated suitable sowing and transplanting dates; in comparison with a comprehensive set of field data.

2. Materials and Methods

2.1. Description of Datasets and Agroecological Zones

The input datasets for driving model system include cultivar, soil property, planting method, and weather data at agro-ecological zones. The main parameters used as input values for the rice model system are shown in Table 1. A wide range of scenarios (seven agro-ecological zones, six cultivars, four planting methods and three climate year types) were used to simulate suitable sowing and transplanting dates for rice using 37 years of weather data. The weather data was categorized into three climatic year types using polynomial fitting approaches [30]. The years of negative and positive anomaly were defined as cool and warm years respectively, while other years were defined as normal years in this study. On this basis, the weather data was classified into three types (cool, warm, and normal years) to predict planting dates. By analyzing the weather data before sowing
in this year, the climate year type is selected to simulate planting dates. The climatic characteristics of agro-ecological zones in this study during the period 1972–2008 are showed in Table 2. The field experiments were carried out with three cultivars, three planting methods, two fertility soil levels, and two management practices at three agro-ecological zones from 2008 to 2010, detailed in Table 3. Zhongzheyou 1, Wuxiangjing 14, and Wuyunjing 19 rice were planted in Xinchang, Rugao, and Wujian, respectively. Moreover, the soil was defined as at low fertility and high fertility levels according to the yield of previous crop. Other field management practices referred to high yield practices recommended by local agricultural experts. While the daily weather data for Wujian, Xinchang and Rugao were acquired from the local meteorological bureau, all other weather datasets downloaded from the National Meteorological Information Center of the China Meteorological Administration (https://data.cma.cn/). Cultivar parameters and high yield strategies recommended by local agricultural experts were assembled from literatures (Table 4) and local agro-technical extension departments. The models will be validated by independent dataset collected from literatures (Table 4), meanwhile the field experiments’ data were used to test the effect of the planting dates simulated by models (Table 3).

Table 2. The climate characteristics of sites.

| Site     | E°1       | NL°2   | AAR 3(mm) | AATmax 4(°C) | AATmin 5(°C) | AAT 6(°C) |
|----------|-----------|--------|-----------|--------------|--------------|-----------|
| Xuzhou   | 117°17’   | 34°11’ | 847       | 28.9         | 0.9          | 16.5      |
| Wujian   | 120°35’   | 31°12’ | 1094      | 30.8         | 5.8          | 18.5      |
| Hangzhou | 120°08’   | 30°13’ | 1200      | 32.0         | 5.5          | 19.0      |
| Chengdu  | 104°01’   | 30°38’ | 918       | 28.6         | 7.2          | 18.0      |
| Nanchang | 115°52’   | 28°38’ | 1611      | 31.8         | 7.0          | 19.5      |
| Xinchang | 120°35’   | 31°12’ | 1300      | 33.2         | 4.5          | 18.5      |
| Rugao    | 120°34’   | 32°22’ | 1074      | 29.8         | 2.9          | 16.5      |

1 E, East longitude; 2 NL, Northern latitude; 3 AAR, Average of annual Rainfall; 4 AATmax, Average of annual maximum temperatures; 5 AATmin, Average of annual minimum temperature; 6 AAT, Average of annual temperature.
Table 3. The results of field experiment at different agro-ecological zones during 2008–2010.

| Site     | PM 1 | Strategy | ST 2 | Grain Yields and Yield Components | PN 3 | GN 4 | SSR 5 | GW 6 | GY 7 | IR 8 |
|----------|------|----------|------|-----------------------------------|------|------|-------|------|------|------|
| Xinchang | AT 13| LF-M 9   | 5/15 (6/14) | 226.9 225.8 83.8 26.8 11506.3 5.5 |
|          |      | LF-E 10  | 5/18 (6/14) | 203 227.5 81.1 26 9738 - |
|          |      | HF-M 11  | 5/15 (6/14) | 215.2 216.8 89.2 26.8 11150 3.9 |
|          |      | HF-E 12  | 5/18 (6/14) | 208.8 206.3 85.6 26.7 9845 - |
| Rugao    | DS 14| LF-M 9   | 6/6 314.3 107.4 92.1 25.8 8016.8 1.3 |
|          |      | LF-E 10  | 6/8 333.5 100.2 92.3 24.9 7680.2 - |
|          |      | HF-M 11  | 6/6 300.3 125 91.6 25.5 8764.9 0.8 |
|          |      | HF-E 12  | 6/8 326 110.9 92.1 25.6 8526.2 - |
| Wujian   | MT 15| LF-M 9   | 5/24 (6/13) | 357 128.6 91.3 26.5 11127 4.6 |
|          |      | LF-E 10  | 5/25 (6/17) | 328.5 124 91.3 25.9 9641.2 - |
|          |      | HF-M 11  | 5/24 (6/13) | 357 130.8 91.9 26.4 11343 2.4 |
|          |      | HF-E 12  | 5/25 (6/17) | 345 125.4 91.2 26.6 10507.8 - |

1 PM, Planting method; 2 ST, Sowing and transplanting date (month/date); 3 PN, Panicle number (10^4 ha^-1); 4 GN, Grain number panicle^-1; 5 SSR, Seed-setting rate (%); 6 GW, 1000-grain weight (g); 7 GY, Grain yield (kg ha^{-1}); 8 IR, Increment rate of grain yield (%).

Table 4. Sowing and transplanting dates recommended by local agricultural experts.

| Site       | Cultivar       | Type         | Reference | PM 1     | SD 2     | TD 3     |
|------------|----------------|--------------|-----------|----------|----------|----------|
| Xuzhou     | Xudao 4        | Japonica     | [31]      | Transplanting | 4/25–5/10 | 6/1–6/10 |
| Wujian     | Wuyunjing19    | Japonica     | [33]      | Transplanting | 5/22–6/2  | 6/10–6/20 |
| Hangzhou   | Yongyou8       | Japonica     | [35]      | Transplanting | 5/20–6/10 | 6/10–6/23 |
| Chengdu    | Wanyou6        | Indica       | [37]      | Transplanting | 3/25–4/10 | 4/20–5/5  |
| Rugao      | Wuxiangjing14  | Japonica     | [39]      | Transplanting | 5/15–5/20 | 6/15–6/20 |
| Xinchang   | Zhongzheyou1   | Indica       | [41]      | Transplanting | 5/15–5/25 | 6/15–6/25 |
| Nanchang   | Ganzaoxian 53  | Indica       | [43]      | Transplanting | 3/20–3/30 | 4/20–4/30 |
|            | Ganxin 688     | Indica       | [45]      | Transplanting | 6/15–6/23 | 7/15–7/23 |

1 PM, Planting method; 2 SD, Sowing date (month/date); 3 TD, Transplanting date (month/date).

2.2. Model Description

In this study, the cultivar, planting method and photoperiod parameters were added to the GDD model [46]. A new rice model system was developed by integrating sowing date model and transplanting date model on the basis of analysis of the interaction of their effects (Figure 1). Abbreviations of the variable parameters are listed in Table 5.
1. Introduction

Breast cancer (BC) corresponds to the most frequent tumor type in women [1]. Nearly 30% of women initially diagnosed with early-stage BC will go on to develop metastatic lesions [2]. Disease progression and the appearance of a disseminated disease have a negative impact on the survival of these patients, being metastases responsible for 90% of deaths related to cancer [3]. Despite the positive impact of new systemic therapies incorporated to the clinic in recent years, metastatic breast cancer (MBC) remains as an incurable disease. Currently, treatment selection is mainly based on the histological characterization of a biopsy from the primary tumor or metastatic sites. However, tissue biopsies have inherently associated limitations such as restricted access and lack of representation of intratumoral heterogeneity, making them an unfeasible approach for long term disease monitoring [4]. Therefore, less invasive techniques with the capacity to predict patient clinical outcome and to guide the treatment are needed in order to better select the more convenient therapy.

Circulating tumor cells (CTCs), those cells shed into the bloodstream by both primary and metastatic tumors, are the main responsible for metastases formation at distant sites. CTCs have therefore the potential to serve as a liquid biopsy. The analysis of CTCs represents a non-invasive procedure that can be serially repeated in order to assess tumor progression in real time, and CTC enumeration may hold promise for improving cancer treatment. CTCs are frequently detected in the peripheral blood of patients with MBC but rarely found in early BC [5-7]. The prognostic value of CTCs in MBC is extensively studied and has been corroborated by large studies. Thus, a CTC count of $\geq$ 5 cells per 7.5 ml blood detected by the CellSearch® system is an independent predictive factor of worse progression-free survival (PFS) and overall survival (OS). First evidences in this regard were shown in 2004 [8] and since then, many studies have confirmed these findings [9-13]. The highest level of evidence has been shown in a recent pooled analysis of individual patient data gathered from 1944 patients demonstrating the clinical validity of CTC enumeration and that CTC count improves

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**Table 5. Abbreviations of the variable parameters.**

| Abbreviations | Description | Unit |
|---------------|-------------|------|
| SSD | Suitable sowing date | d |
| GDDsh | Growing degree days from sowing to heading | °C·d |
| GDDsh(I) | Growing degree days of indica rice from sowing to heading | °C·d |
| GDDsh(J) | Growing degree days of japonica rice from sowing to heading | °C·d |
| FWS | Calibrating parameter of fertilizer and water status | |
| Ssd | Safe sowing date | d |
| Esd | Expected sowing date | d |
| Sfhs | Full heading stage | |
| FHd | Date of full heading | d |
| Ehd | Expected harvest date | d |
| Ehp | Expected harvest period of the previous crop | d |
| N | Total leaf number of main stem | |
| n | Total internode number of main stem | |
| k | Calibrating parameter of planting method | |
| DL | Day-length | h |
| STD | Suitable transplanting date | d |
| GDDst | Growing degree days from sowing to transplanting | °C·d |
| GDDst (I) | Growing degree days of indica rice from sowing to transplanting | °C·d |
| GDDst (J) | Growing degree days of japonica rice from sowing to transplanting | °C·d |
| Std | Safe transplanting date | d |
| Etd | Expected transplanting date | d |
| HFD | Optimal heading and filling date | d |
| FHd | Date of full heading | d |
| Ehd | Expected harvest date | d |
| $\theta$ | The parameter of seedling | |
| GYT | Grain yield target | kg ha$^{-1}$ |
| $G_{Y_{max}}$ | Maximum historical grain yield of agro-ecological zones | kg ha$^{-1}$ |
2.2.1. Algorithms to Determine Suitable Sowing Date

Previous studies have shown that the optimal temperature of heading and filling was related to cultivar type (japonica (Vj), indica (Vi), japonica hybrid (Vjh), indica hybrid (Vih)), cropping system (single-cropping rice (Fs), double-cropping early rice (Fde), double-cropping late rice (Fdl)), and fertilizer and water status [47,48]. Generally, the optimal temperature during the heading and filling stages ranged from 30 °C to 33 °C [22]. Japonica rice is better adapted to low temperature, while indica rice prefers high temperature for ripening [22]. Late rice is better adapted to low temperature, while early rice prefers high temperature [49]. The date (converted into Julian day [50]) when the optimal temperature appears is the optimal heading and filling date (HFD) of rice. HFD was calculated as follows:

\[
\text{HFD} = \begin{cases} 
\text{Dt30} & V = Vj \\
\text{Dt31} & V = \text{Vjh or Vih} \text{ and } F = \text{Fdl} \\
\text{Dt32} & V = \text{Vjh or Vih} \text{ and } F = \text{Fs} \\
\text{Dt33} & V = \text{Vi or V} \text{ and } F = \text{Fde} 
\end{cases}
\]

where Dt30, Dt31, Dt32, and Dt33 are starting dates of the Julian day, when the daily mean temperature in a row 5 Julian days remain stable at 30 °C, 31 °C, 32 °C, and 33 °C, respectively [51].

The GDD varies with rice phenology [52]. Although light and temperature are the major factors determining phenological development, cultivar differences, diverse environmental factors, and cultural practices also have impacts [25]. The GDD during the period from sowing to heading (GDDsh) is related to the total number of leaves on the main stem [53]. GDDsh is the number of inclusive growing degree days from sowing date to heading. This is a relatively stable parameter [54]; there are also slight differences over the different planting methods [55]. There was no significant difference among cultivars within the parameter values within the same subspecies, but there was a significant difference between indica rice and japonica rice [46]. Therefore, the mean values of each cultivar parameter within same subspecies are taken as the parameter value in two rice subspecies models (GDDsh(I) and GDDsh(J)), respectively [46]. GDDsh varies with planting method, fertilizer, and water management of different agro-ecological zones [25]. Therefore, planting method, fertilizer, and water management factors were added in the simulation model developed by Feng et al. [46]. There is a linear relationship between the GDD required for rice growth and leaf age before three-leaf stage [46]. During the period from sowing to three-leaf stage, the GDD values of indica rice (both Vi and Vih) and japonica rice (including Vj and Vjh) are 100.2 and 115.8, respectively. These new models were calculated as follows:

\[
\text{GDDsh}(I) = 100.2 + \sum_{i=3}^{N-n-2} ((i-3) \times 0.36 + 42.1) + \sum_{i=N-n-2}^{N-n-1+k} \left( 50.1 \times e^{0.29-0.009N \times (i-N+n+2)} \right) \\
\text{GDDsh}(J) = 115.8 + \sum_{i=3}^{N-n-2} ((i-3) \times 1.74 + 52.8) + \sum_{i=N-n-2}^{N-n-1+k} \left( 62.7 \times e^{0.27-0.007N \times (i-N+n+2)} \right)
\]

\[
\text{GDDsh} = \frac{\text{GDDsh}(\alpha)}{\text{FWS}} \quad \alpha = I \text{ or } J
\]

where i is the leaf age of main stem varies with seedling growth, and GDDsh(I) and GDDsh(J) represent the GDD of indica rice (both Vi and Vih) and japonica rice (including Vj and Vjh) from sowing to heading, respectively. In Equations (2) and (3), N stands for total leaf number of main stem, n denotes total internode number of main stem, and k is the calibrating parameter of planting method in this study. The k values of manual transplanting, mechanized transplanting or seedling throwing, and direct sowing are 1, 0, −1, respectively. The FWS (Equation (4)) is the parameter of fertilizer and water management level of the agro-ecological zone [56]. By calculating the FWS value, the organic matter content, calcium carbonate content, potential of hydrogen, salinity, and groundwater table
were entered to the soil modification coefficient model \([57]\). The \(s\) is quantified by Equation (5) as a photoperiod parameter.

\[
s = 1.5662 \times (1 - e^{-0.10782 \times DL})
\]  

where \(DL\) is day length related to latitude and solar altitude angle \([58]\). When determining the suitable sowing date of single-cropping or double-cropping early rice, the dates simulated by the model must ensure that rice seed can emerge safely and be sown in a timely manner after the safe sowing date \((Ssd)\). Krishnan et al. indicated a minimum daily mean temperature of 16 °C, 17 °C, and 18 °C for germination of japonica, indica, and hybrid rice cultivars, respectively \([22]\). For a germination of 90% or higher, the incubation time at temperatures between 15 and 37 °C was about 6 days \([22]\). The safe sowing date \((Ssd)\) was calculated as follows:

\[
Ssd = \begin{cases} 
Dt16 & V = Vj \\
Dt17 & V = Vi \\
Dt18 & V = Vih \text{ or } Vjh 
\end{cases}
\]  

where \(Dt16\), \(Dt17\), and \(Dt18\) represent are starting dates of the Julian day, when the daily mean temperature in a row 6 Julian days remains above 16 °C, 17 °C, and 18 °C, respectively \([22]\). In Equation (7), when \(SSD \geq Ssd\), the seed can emerge safely, otherwise, the date is postponed to \(Ssd\). These scores were calculated as follows:

\[
SSD = \begin{cases} 
SSD & SSD \geq Ssd \\
Ssd & SSD < Ssd
\end{cases}
\]  

When \(SSD = Ssd\), rice can reach full heading at safe full heading stage \((Sfhs)\). When the GDD during the period from \(Ssd\) to the date of full heading \((FHd)\) is equal to GDD\(_{s}h\), FHd is calculated. Safe completion of full heading is judged by comparing the date of full heading \((FHd)\) and \(Sfhs\) when \(SSD\) is postponed to \(Ssd\). When \(Sfhs \geq FHd\), rice can complete full heading safely, otherwise it is not the suitable sowing date or the suitable cultivar for this agro-ecological zone.

Crop models and regional expertise are effective means to improve agricultural production. The crop model and expert suggestion are different choice for helping farmers’ field production. For direct sowing, the expected harvest date \((Ehd, \text{Equation } (8))\) and expected harvest period of the previous crop \((Ehp, \text{Equation } (8)\) during the period from the beginning of crop harvest to the end of field preparation for next crop) should be considered. According to \(Ehd\) and \(Ehp\), the expected sowing date \((Esd)\) for direct sowing is quantified by Equation (8). In Equation (9), when \(SSD \geq Esd\), SSD is used. Otherwise, \(Esd\) is used as the suitable sowing date for direct sowing.

\[
Esd = Ehd + Ehp
\]  

\[
SSD = \begin{cases} 
SSD & SSD \geq Esd \\
Esd & SSD < Esd
\end{cases}
\]  

2.2.2. Algorithms to Determine Suitable Transplanting Date

Transplanting rice at the right time is key to achieve high yield under suitable sowing dates. The three-leaf stage of seedling is a critical phase of the rice plant. After the three-leaf stage, rice seedlings become self-sustaining through nutrient intake by roots and photosynthesis. Prior to this, seedlings are highly susceptible to volatile environmental conditions \([48]\). The dynamic relationship between leaf age and GDD of rice should be divided into three stages (sowing to three-leaf stage, three-leaf stage to stagnation of tillering, and after stagnation of tillering) to develop model \([46]\). Generally, the seedlings are transplanted during the period between three-leaf stage and stagnation of tillering \([48,56]\). GDD\(_{dst}\) is the number of inclusive growing degree days from sowing date to transplanting date. Based on
the relationship between leaf age and GDD for each cultivar, the GDD from suitable sowing date to transplanting (GDDst) was calculated as follows:

\[
\text{GDDst}(I) = 100.2 + \sum_{i=3}^{\text{max}(\text{LN},3)} ((i-3) \times 0.6 + 42.1)
\]

(10)

\[
\text{GDDst}(J) = 115.8 + \sum_{i=3}^{\text{max}(\text{LN},3)} ((i-3) \times 1.74 + 52.8)
\]

(11)

\[
\text{GDDst} = \frac{\text{GDDst}(\alpha)}{\text{FWS}} \quad \alpha = I \text{ or } J
\]

(12)

where \(i\) is the leaf age of main stem varies with seedling growth; \(\text{GDDst}(I)\) and \(\text{GDDst}(J)\) represent GDD of indica and japonica rice from sowing to transplanting, respectively. FWS expresses the same meaning in Equations (4) and (12). Planting methods have significant influence on the suitable transplanting date and the value of LN was related to planting methods and yield [48]. LN is the parameter for leaf age of seedling calculated as follows:

\[
\text{LN} = \theta \times \min(Y_i, 1)
\]

(13)

where \(\theta\) is the parameter of seedling. For manual transplanting, \(\theta\) is 6.8 and 5.5 for wet seedlings and dry seedlings respectively, and 3.8 and 4.5 for mechanical transplanting and seedling throwing, respectively. \(Y_i\) is a calibrating parameter of grain yield target calculated as follows:

\[
Y_i = 0.75 + 0.25 \times \frac{\text{GYT}}{\text{GY}_{\text{max}}}
\]

(14)

where GYT is grain yield target [58]. The GYT values is set by users. The GYT values threshold in the model was changed from the maximum to the minimum historical grain yield of an agro-ecological zone. \(\text{GY}_{\text{max}}\) is the maximum historical grain yield of an agro-ecological zone. The suitable transplanting date of single-cropping or double-cropping rice determined by the model must ensure that seedlings can be transplanted safely. These critical temperatures may vary with cultivar and cultural management practices [22]. The critical minimum daily mean temperature for root elongation is about 16 °C and that for tillering from 9 to 16 °C [22]. Moreover, 16 °C can meet the temperature need of root elongation and tillering simultaneously. Dt16 is starting dates of the Julian day, when the daily mean temperature in a row 6 Julian day remains above 16 °C. Dt16 is set to safe transplanting date (Std, Equation (15)) for all scenarios. In Equation (16), when \(\text{STD} \geq \text{Std}\), the suitable transplanting date (STD) is acceptable, otherwise, STD will be postponed to the safe transplanting date (Std, Equation (15)).

\[
\text{Std} = \text{Dt16}
\]

(15)

\[
\text{STD} = \begin{cases} \text{STD} & \text{STD} \geq \text{Std} \\ \text{Std} & \text{STD} < \text{Std} \end{cases}
\]

(16)

To ensure the timely transplanting of rice at STD, Ehd (Equation (8)), and Ehp (Equation (8)) of the previous crop should be considered. The expected transplanting date in rice (Etd, Equation (17)) is determined by Ehd (Equation (8)) and Ehp (Equation (8)). When \(\text{STD} \geq \text{Etd}\), the suitable transplanting date is reasonable, otherwise, Etd should be the suitable transplanting date. These scores were calculated as follows:

\[
\text{Etd} = \text{Ehd} + \text{Ehp}
\]

(17)

\[
\text{STD} = \begin{cases} \text{STD} & \text{STD} \geq \text{Etd} \\ \text{Etd} & \text{STD} < \text{Etd} \end{cases}
\]

(18)
2.3. Model Evaluation Method

We evaluated the performance of the new rice model system by simulating sowing and transplanting dates using statistical methods and graphical presentations. The intercept ($\beta$), slope ($\alpha$), and coefficient of determination ($R^2$) of linear regression between observed and simulated values were determined. For sowing and transplanting dates, we also compared paired data-points for simulated and observed values using linear regression. The standard deviation (SD), Student’s t-test of means assuming unequal variance ($P(t)$) and RMSE (Equation (19)) were used to evaluate the performance of this model. As a tool to test the measure of fit, the model efficiency (EF) is defined by Equation (20) [10].

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}}$$  \hspace{1cm} (19)

$$\text{EF} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2}$$ \hspace{1cm} (20)

where $O_i$ is the observed value, $S_i$ is the simulated value, $\bar{O}_i$ is the mean of observed values, and $n$ is the number of data pairs. Ideally, $\beta$ and RMSE should be approximately 0, and $P(t)$ should be higher than 0.05 at 95% confidence level. Meanwhile, $\alpha$, EF, and $R^2$ should be approximately 1. Ideally, RMSE between observed and simulated values should be less than SD of observed values.

3. Results

3.1. Simulation of Sowing and Transplanting Dates

The sowing and transplanting dates simulated by the model across different pedoclimatic scenarios are listed in Table 6. The ideal sowing and transplanting windows for high yields, which were recommended by local agricultural experts for each agroecological zone, are broken down by planting method in Table 4. The cultivar parameters ($N$ and $n$) derived from literatures and breeding experts. The weather parameters ($s$ and DL) and temperature downloaded from the National Meteorological Information Center of the China Meteorological Administration (https://data.cma.cn/). Before simulating planting dates, the values of $k$, $i$, $E_{hd}$, $\theta$, and $FWS$ were set by referring to the field experiments descriptions in the references (Table 4). The GYT and $GYT_{max}$ were set by referring to the results of field experiment in the references (Table 4). The sowing and transplanting dates were simulated for six cultivars (Table 4) in five sites (Table 6). In each site, each rice cultivar is planted across four planting methods, and the planting dates simulated by the model. We simulated sowing and transplanting dates for three climatic years under different planting methods and cultivars in each site.
Table 6. Simulation of sowing and transplanting dates under different scenarios.

| Site       | Manual Transplanting | Mechanized Transplanting | Seedling Throwing | Direct Sowing |
|------------|----------------------|--------------------------|-------------------|--------------|
|            | WY 1  | NY 2  | CY 3 | WY 1  | NY 2  | CY 3 | WY 1  | NY 2  | CY 3 | WY 1  | NY 2  | CY 3 |
| Xuzhou     | 5/11  | 5/6   | 5/1  | 5/15  | 5/12  | 5/10 | 5/15  | 5/12  | 5/10 | 6/13  | 6/7   | 6/4 |
|            | (6/13) | (6/11) | (6/9) | (6/11) | (6/10) | (6/10) | (6/13) | (6/13) | (6/12) |            |     |
| Wujiang    | 5/20  | 5/18  | 5/14 | 5/26  | 5/24  | 5/22 | 5/26  | 5/24  | 5/22 | 6/15  | 6/10  | 6/8 |
|            | (6/16) | (6/15) | (6/13) | (6/14) | (6/13) | (6/12) | (6/15) | (6/15) | (6/14) |            |     |
| Hangzhou   | 5/24  | 5/20  | 5/16 | 5/27  | 5/25  | 5/23 | 5/27  | 5/25  | 5/23 | 6/16  | 6/11  | 6/7 |
|            | (6/19) | (6/17) | (6/15) | (6/16) | (6/15) | (6/14) | (6/16) | (6/17) | (6/16) |            |     |
| Chengdu    | 3/19  | 3/13  | 3/9  | 3/26  | 3/23  | 3/22 | 3/26  | 3/23  | 3/22 | 4/22  | 4/15  | 4/12 |
|            | (4/23) | (4/19) | (4/16) | (4/19) | (4/18) | (4/18) | (4/21) | (4/20) | (4/20) |            |     |
| Nanchang   | 5/22  | 3/25  | 3/21 | 4/8   | 4/5   | 4/3  | 4/8   | 4/5   | 4/3  | 4/30  | 4/28  | 4/25 |
|            | (4/25) | (4/22) | (4/20) | (4/22) | (4/21) | (4/21) | (4/23) | (4/22) | (4/22) |            |     |
|            | 6/22  | 6/18  | 6/15 | 7/3   | 7/1   | 6/29 | 7/3   | 7/1   | 6/29 | 7/24  | 7/22  | 7/19 |
|            | (7/16) | (7/14) | (7/13) | (7/16) | (7/15) | (7/14) | (7/17) | (7/16) | (7/15) |            |     |

1 WY, Warm year; 2 NY, Normal year; 3 CY, Cool year; 4 (). The dates in parentheses are the transplanting dates.

3.2. Model Validation

Data from literatures and field experiments were used to validate the model system under different scenarios. Scatter diagrams of observed against simulated variables for six cultivars, three climatic years, and four planting methods are shown in Figure 2. Most of the simulated sowing and transplanting dates were close to the 1:1 line and indicated that the practices designed by the model matched well with the high yield practices recommended by local agricultural experts. Modelling efficiency (EF) greater than 0.7 and R² greater than 0.85 between observed and simulated values in all cases showed that sowing and transplanting dates simulated by the new rice model system were acceptable (Table 7). The standard deviation (SD) of the observed values were 2–3 times more than the root mean square error (RMSE) between observed and simulated values (Table 7). Student’s paired t-test of means assuming unequal variance P(t) indicated that 7 of the 21 simulated dates were not significantly different from the observed values at 95% confidence level (Table 7). Simulated sowing and transplanting dates for manual transplanting in all climatic years were below the 1:1 line, which suggests that the model recommended dates for manual transplanting were too early. Simulated sowing dates for direct sowing in warm and normal climatic years were above the 1:1 line, which suggests that the model recommended dates for direct sowing were too late. Simulated transplanting dates in cool climatic years were below the 1:1 line, which suggests that the model recommended dates for transplanting were too early. The above results were supported by Student’s paired t-test (P(t) < 0.05) at 95% confidence level. The intercept (α) of sowing and transplanting dates under different scenarios were close to 1 in all climatic years, which indicates a good fit between simulated and observed data.

Although 14 of the 21 simulated dates were significantly different from observed dates demonstrated by P(t), fraction of simulated dates were within the suitable window for the region recommended by local agricultural experts (Figure 2). Simulated sowing dates for Ganxin 688 in all climatic years were above the 1:1 line under mechanized transplanting and seedling throwing. Simulated sowing dates for Wanyou 6 in all climatic years were below the 1:1 line, except for direct sowing. Simulated sowing dates for Yongyou 8, under direct sowing and manual transplanting, were above and below the 1:1 line, respectively, in all climatic years. This may be primarily because these cultivars are not suitable for these planting methods.

Combined analysis of grain yield under different scenarios indicated that the panicle number per unit area and grain number per panicle with the model practices generally increased by 1.5% and 4.5%, respectively, and the seed-setting rate and 1000-grain weight increased by 1.2% and 1.3%, respectively, compared with the local experts’ practices. The results indicated that these model practices increased...
yield by 0.8–5.5%, compared with the local experts’ practices. The yield of manual transplanting in low fertility soil increased most significantly (5.5%), while that of direct sowing in high fertility soil was increased slightly (0.8%).

Figure 2. Comparison between observed and simulated sowing dates in red and transplanting dates in blue for rice under different planting methods, climatic years and cultivars. SD, line of linear regression between observed and simulated values for sowing dates; TD, line of linear regression between observed and simulated values for transplanting dates. Short dashed lines are the 1:1 relationship lines. W, Warm year; N, Normal year; C, Cool year. For example, mechanized-transplanting-W means sowing and transplanting dates for mechanized transplanting rice in warm year.
4. Discussion

Compared with the existing rice cultivation and management techniques [55], this rice model system objectively considers different factors such as climate, soil, and cultivar. This strategy could be very useful for simulating suitable sowing and transplanting dates under various climate change scenarios [39,60]. The new rice model system effectively combines the decision-making performance of expert system with the dynamic forecasting ability of crop simulation model and overcomes the shortcomings of strong regionalism and subjective localized experience in decision-making. This solves the problems of strong regionalism, strong experience, and weak quantification of conventional agricultural expert systems. The model can be used for strategic-scale decision-making in rice production management over different ecological conditions and technology levels. Compared with the practices of the existing rice models [56], this model has wider applicability and higher precision in determining sowing and transplanting dates reliably across different scenarios.

We observed statistical differences between simulated and observed values at 95% level under certain scenarios. Nevertheless, coefficient of determination (R²) indicated a strong correlation across all scenarios. Cui et al. [51] analyzed the variations of thermal growing season in northern China during the period 1961–2015 and found the length of the growing season had averaged extended about 15.5–16.0 days with altitudes range from 0 to 1000 m, and 17.8–20.2 days with altitudes range from 2500 to 4000 m. In our study, RMSE range from 5.3 to 14.74 days indicated that the sowing and transplanting dates model system has well simulation performance across all scenarios. The model performed better in simulating sowing dates for mechanized transplanting and seedling throwing than other planting methods, and better in simulating transplanting dates for manual transplanting in warm years and seedling throwing in warm and normal years than other scenarios. For Wanyou 6, the simulated sowing dates were underestimated for all planting methods except for direct sowing. Similarly, the simulated sowing dates were underestimated for direct sowing and manual transplanting.

### Table 7. Evaluation results of the rice model system across different scenarios.

| PM ² | Year | Date | N ³ | X_{obs} ⁴( SD) | X_{sim} ⁵( SD) | P(t) ⁶ | A ⁷ | B ⁸ | R² ⁹ | RMSE ¹⁰ | EF ¹¹ |
|------|------|------|-----|----------------|----------------|--------|------|-----|------|--------|------|
| WY ¹⁶ | Sowing | 87 | 128(30.0) | 124(32.4) | 0.00 | 1.04 | -9.2 | 0.93 | 9.72 | 0.89 | |
| | Transplanting | 71 | 151(29.6) | 151(30.7) | 0.63 | 1.02 | -2.9 | 0.97 | 5.30 | 0.97 | |
| AT ¹² | Sowing | 87 | 128(30.0) | 120(32.0) | 0.00 | 1.02 | -10.0 | 0.91 | 11.97 | 0.84 | |
| | Transplanting | 71 | 151(29.6) | 149(31.5) | 0.00 | 1.05 | -9.4 | 0.97 | 6.18 | 0.96 | |
| CY ¹⁸ | Sowing | 87 | 128(30.0) | 116(32.2) | 0.00 | 1.03 | -14.9 | 0.92 | 14.74 | 0.76 | |
| | Transplanting | 71 | 151(29.6) | 147(32.0) | 0.00 | 1.06 | -13.9 | 0.97 | 7.56 | 0.94 | |
| WY ¹⁶ | Sowing | 87 | 128(30.0) | 131(30.8) | 0.01 | 0.97 | 6.5 | 0.89 | 10.45 | 0.88 | |
| | Transplanting | 71 | 151(29.6) | 149(31.7) | 0.00 | 1.06 | -10.7 | 0.98 | 6.03 | 0.96 | |
| MT ¹³ | Sowing | 87 | 128(30.0) | 128(31.2) | 0.61 | 0.99 | 2.1 | 0.90 | 9.90 | 0.89 | |
| | Transplanting | 71 | 151(29.6) | 148(31.7) | 0.00 | 1.06 | -11.7 | 0.97 | 6.47 | 0.95 | |
| CY ¹⁸ | Sowing | 87 | 128(30.0) | 126(30.9) | 0.23 | 0.98 | 1.3 | 0.90 | 9.76 | 0.89 | |
| | Transplanting | 71 | 151(29.6) | 147(31.3) | 0.00 | 1.04 | -10.1 | 0.97 | 6.68 | 0.95 | |
| WY ¹⁶ | Sowing | 87 | 128(30.0) | 131(30.8) | 0.01 | 0.97 | 6.5 | 0.89 | 10.44 | 0.88 | |
| | Transplanting | 71 | 151(29.6) | 150(31.4) | 0.11 | 1.04 | -7.8 | 0.97 | 5.63 | 0.96 | |
| ST ¹⁴ | Sowing | 87 | 128(30.0) | 128(31.2) | 0.61 | 0.99 | 2.1 | 0.90 | 9.90 | 0.89 | |
| | Transplanting | 71 | 151(29.6) | 150(31.8) | 0.05 | 1.06 | -9.9 | 0.97 | 6.02 | 0.96 | |
| CY ¹⁸ | Sowing | 87 | 128(30.0) | 126(30.9) | 0.23 | 0.98 | 1.3 | 0.90 | 9.76 | 0.89 | |
| | Transplanting | 71 | 151(29.6) | 149(31.3) | 0.00 | 1.04 | -8.2 | 0.97 | 5.95 | 0.96 | |
| WY ¹⁶ | Sowing | 56 | 146(30.0) | 155(29.1) | 0.00 | 1.04 | -16.8 | 0.94 | 11.37 | 0.85 | |
| | Transplanting | 71 | 151(29.6) | 150(31.8) | 0.05 | 1.06 | -9.9 | 0.97 | 6.02 | 0.96 | |
| DS ¹⁵ | Sowing | 56 | 146(30.0) | 155(29.1) | 0.00 | 1.04 | -8.2 | 0.97 | 5.95 | 0.96 | |

¹ PM, Planting method; ² N, Number of data pairs; ³ X_{obs}, Mean observed values of Julian days; ⁴ SD, Standard deviation; ⁵ X_{sim}, Mean simulated values of Julian days; ⁶ P(t), Significance of Student’s paired t-test at 95% confidence level; ⁷ β, Slope of linear regression between observed and simulated values; ⁸ β', Intercept of linear relation between observed and simulated values; ⁹ R², Square of linear correlation coefficient between observed and simulated values; ¹⁰ RMSE, Absolute root mean square error; ¹¹ EF, Modelling efficiency as recognized measure of fit. ¹² AT, Mechanized transplanting; ¹³ MT, Manual transplanting; ¹⁴ ST, Seedling throwing; ¹⁵ DS, Direct sowing; ¹⁶ WY, Warm year; ¹⁷ NY, Normal year; ¹⁸ CY, Cool year.
for Yongyou 8, and overestimated for mechanized transplanting and seedling throwing for Ganxin 688. However, \( R^2 \) manifested a strong correlation between simulated and observed values across all scenarios.

It may be due mainly to the fact that not all cultivars are suitable for all planting methods, or that the planting dates for increasing yield recommended by local experts are not optimal. Compared with the growth days of manual transplanting rice, the average growth days of seedling throwing and mechanized transplanting rice were shortened by 4.9 days and 10.3 days, respectively [29]. The utilization efficiency of sunshine duration and growing degree days (GDD) in rice under different planting methods during the growing period showed that manual transplanting > seedling throwing > mechanized transplanting [29]. Liu et al. [61] indicated a variable grain yield response dependent on cultivar and agroecological environment. Compared with the experts’ practices, the model practices show that 0.8–5.5% grain yield increases from the field experiments could have been achieved. Hence, the results of field experiments demonstrated that the sowing and transplanting dates recommended by local experts were not entirely suitable.

The suitable sowing and transplanting dates are vulnerable to variable weather conditions, and could be impacted by hot temperatures during flowering and grain filling stages [62]. Adjustment of planting dates and selection of heat-tolerant cultivars to mitigate the influence of temperature change should be applied to avoid heat stress effects on rice production [18]. Optimizing planting date would increase yield potential by capturing more rainwater, solar radiation and favorable temperatures for growth during the growing season [63]. In Pakistan, the flow of water in irrigation canals remains below its capacity in hot months of June to July and most farmers have to irrigate rice at 4–8 day intervals [64]. Therefore, the most farmers in Pakistan start sowing rice nursery in early April, and transplanting seedlings in mid-May to avoid the water shortage to reduce irrigation frequency during peak summer season, and escape from the pests’ attack thereby to reduce the additional cost of inputs as a result of pesticide application [16]. Thus, developing suitable sowing and transplanting dates practices are crucial for reducing climate risks and increasing resources use efficiency. However, the suitable sowing and transplanting dates recommended by local experts were quite static. Planting dates simulated by the model system varied with increase in temperature (between different climates year, planting method, and cultivar; Table 6). Therefore, this new rice model system can be used dynamically and flexibly to overcome the shortcomings practices recommended by local experts. The practices determined by the model is better than that recommended by the local experts to increase yield in rice, and the model had better reliability and decision-making performance.

Validation of the model system was restricted by spatial and temporal distribution. A more generalized calibration and validation of the model system will require multi-location and multi-year experiments to determine the optimal parameters to further improve accuracy and reliability of the model. Furthermore, there is a need to evaluate integrated ecological and economic benefits of rice management practices determined by the model; for example estimating greenhouse gas emissions from various types of rice production systems [65].

5. Conclusions

Modern software engineering and crop simulation models provide an innovative approach to precision rice farming. By extracting new cultivation knowledge and techniques from agronomic experts and literatures, the model algorithms of suitable sowing and transplanting date were established, and a new rice model system was developed for determining suitable planting date by integrating fundamental model parameters. Model evaluation results showed that the model system has well simulation performance and application performance under different climate, cultivars and management strategies. Compared with local experts’ practices, the planting dates designed by this model system showed a 0.8–5.5% increase in grain yield and higher accuracy and adaptability in the field experiments. Hence, this new rice model system can accurately simulate the suitable sowing and transplanting dates of diverse cultivars for farmers in different rice production zones, and even adjust
planting date for future climate change scenarios. This work can act as a technical approach to achieve high yield and efficiency for farmers.

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