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Simulating the optimal growing season of rice in the Yangtze River Valley and its adjacent area, China

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Abstract

With a focus on the dependence of rice production on climatic conditions, a model was presented to simulate the growth and development of different rice genotypes. Simulations of biomass growth responded to daily solar radiation and temperature for a given genotype. The contributions of photosynthate produced before and after heading to grain yield and the effect of temperature on grain filling were incorporated into the growth model. Simulation of plant phenological development was driven by daily temperature and day-length. Model predictions of biomass accumulation and grain yield formation were validated against field measurements and good agreement between simulated and observed data sets was obtained. By applying the developed model to the Yangtze River Valley and its adjacent area, which covers approximately 70% of the total rice cropping area in China, the optimal growing seasons under local climatic conditions and cropping systems were simulated and the relevant grain yields were predicted for four rice genotypes (hybrid *indica*, medium *indica*, medium *japonica* and late *japonica*). Simulations showed that the optimal sowing dates are between 10 April and 20 May and the corresponding heading dates occur in the period from the end of July to the end of August. The simulated grain yields under these optimal growing seasons vary from a value of 7.90–11.25 t/ha. Observations from various locations indicated that grain yields obtained within the optimal planting period were higher than those outside the optimal period. Calculations suggested that an average increase of 10% in grain yield is possible when rice plants are planted within the simulated optimal period, approximately 10 days earlier than current planting dates. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Rice; Solar radiation; Temperature; Simulated crop growth

1. Introduction

Rice is vital to more than half of the world population. It is the most important food grain in the diets of hundreds of millions of Asians, Africans, and Latin Americans living in the tropics and subtropics (Yoshida, 1981). Projections based on population growth rates in countries where rice is the main crop indicate that rice production must increase approximately 65% from a 1990 value of 473 million tons to 781 million tons by 2020, to meet the rice demand for growing populations (IRRI, 1989). China represents more than 20% of the world population, while its arable land is only some 7% of the world total. There is no doubt that increased yields must be achieved by improved grain yield per unit area rather than an increase in total land area.

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Rice production is affected by sets of varietal and environmental parameters, including genetic characteristics, soil, weather and cultivational management. Rice grain yield for a given cultivar is mainly dependent upon local climatic conditions such as solar radiation and temperature, when plants are grown on the conditions of ample nutrients and water. In other words, the variation in rice production along spatial and temporal gradients would be attributable to different climates when other conditions are suitable for plant growth and development. The different climatic conditions are mostly associated with either cropping regions or cropping seasons in the same year for a particular area. For those regions where a single rice cropping system is predominant and there is more flexibility in the calendar, the determination of the optimal growing season will be of great benefit in increasing grain yield per unit area. The optimal growing season for an already developed cultivar, for a long period, has been determined by changing planting dates with a certain time interval, experiments that generally take 2–3 yr to complete. Due to the variation in weather conditions between years, the results from these experiments create great uncertainties, especially when the weather conditions during the growing season are far from normal. Moreover, such experiments usually cost a lot since they must be conducted over a wide range of cropping area.

With the achievements in crop simulation (McMennamy and O'toole, 1983; Ritchie et al., 1987; Penning de Vries et al., 1989; Williams et al., 1989; Singh et al., 1993; Kropff et al., 1993), it has become possible to solve such agronomic problems as breeding recommendations (Dingkuhn, 1995) and optimizing rice production management (Huang et al., 1996) by applying crop modeling techniques. Dingkuhn and Miezan (1995) presented a field-based model simulating flowering date and chilling-induced spikelet sterility for irrigated rice in the Sahel and suggested that the photothermal response in phenology is an important character for breeding new rice cultivars in arid environments. The simulation also showed that the rice double-cropping calendars currently being followed in that area are mostly without an alternative and offer little temporal flexibility if based on genotypes presently cultivated. Thus, the introduction of alternative short-duration varieties would be required to achieve a greater flexibility for cropping calendars in the Sahel (Dingkuhn, 1995). By combining rice simulation with cultivational decision-making, a software package for optimizing rice production management, mostly dealing with fertilizer application and irrigation schedule, was developed more recently (Huang et al., 1996). This package has been used to help rice farmers make timely adjustments in their cultivational practices and obvious increases in both grain yield and profit have been reported in several irrigated rice cropping regions of China since 1991 (Huang et al., 1996).

Focused on the dependence of rice production on climatic conditions, the authors in this paper deliver a model for simulating rice growth and development. By employing the model, optimal growing seasons for four rice genotypes (hybrid *indica*, medium *indica*, medium *japonica* and late *japonica*) are simulated to intensify rice production in the major rice-growing region of China.

2. Model description

2.1. Growth

Rice crop growth was characterized by the accumulation of biomass and computed by

$$\Delta \mathrm{BIM}_i = 0.58(P_i - R_i) \tag{1}$$

$$\mathrm{BIM}_i = \mathrm{BIM}_{i-1} + \Delta \mathrm{BIM}_i \tag{2}$$

where $\Delta\mathrm{BIM}_i$ is a daily increment of rice biomass (g m^{-2} day^{-1}), a result of photosynthesis minus respiration. P_i and R_i represent daily gross photosynthesis (g CO$_2$ m^{-2} day^{-1}) and respiration (g CO$_2$ m^{-2} day^{-1}) of a rice canopy, respectively. The coefficient 0.58 was derived from two assumed factors: 0.68, the conversion of CO$_2$ to carbohydrate ([CH$_2$O]/[CO$_2$]= 0.68); and 0.85, the conversion of carbohydrate to rice biomass (Qi, 1986) (0.68×0.85=0.58).

On the assumption that nutrients and water are available in ample supply and the crop is free of diseases and insect pests as well as weeds, the daily gross photosynthesis, P_i , was modeled by

$$P_i = \mathrm{TF}_i \frac{B}{kA} \ln\left[\frac{1 + 0.44AR_\mathrm{s}(1-f)}{1 + 0.44AR_\mathrm{s}(1-f)\exp(-kL_i)}\right] D_i \tag{3}$$

In Eq. (3), coefficients A and B are photosynthesis parameters derived from both laboratory and field measurements (Huang et al., 1990). Albedo and light extinction coefficient of a rice canopy are expressed by f and k, respectively. All these four coefficients A, B, f and k are variety-dependent and have different values before and after heading (Huang et al., 1990). The constant 0.44 is the PAR fraction of solar radiation (Begon et al., 1990) and R_s is an average hourly flux density of downward solar radiation (MJ m^{-2}). D_i is day-length in hours computed from an astronomical formula (Jones, 1983). The effect of temperature on photosynthesis, TF_i, was modeled by Eq. (4) and green leaf area index, L_i, was simulated by Eqs. (5)–(7), respectively.

$$\mathrm{TF}_i = \begin{cases} -0.434 + 0.1027\mathrm{TD}_i - 0.00184\mathrm{TD}_i^2 \\ (\text{for } \textit{indica}) \\ -0.623 + 0.1147\mathrm{TD}_i - 0.00203\mathrm{TD}_i^2 \\ (\text{for } \textit{japonica}) \end{cases} \tag{4}$$

where TD_i is an average temperature in daytime (°C), estimated from daily maximum temperature, $T_{\max}$, and daily minimum temperature, $T_{\min}$. $\mathrm{TD}=(T_{\max}+T_{\min})/2+(T_{\max}-T_{\min})/4$.

The extension of leaf area before heading was determined by the photosynthate partitioned to the leaves and the ($n-5$)th leaf in the lower position of the rice canopy was assumed to begin dying when the nth leaf emerged ($n\geq5$). The senescence of leaves after heading was simulated as a function of the developmental index.

$$\Delta L_i = \mathrm{PL}_i(\Delta\mathrm{BIM}_i)(\mathrm{SLA}_i) - \Delta L_{NL-5} \tag{5}$$

$$L_i = L_{i-1} + \Delta L_i \ (\text{before heading}) \tag{6}$$

$$L_i = \frac{L_\mathrm{h}}{1 + a\mathrm{DVI}_i^2} \ (\text{after heading}) \tag{7}$$

ΔL_i in Eq. (5) is a net increment of leaf area index, which is equal to a daily increment, $\mathrm{PL}_i(\Delta\mathrm{BIM}_i)(\mathrm{SLA}_i)$, minus a daily senescence, ΔL_{NL-5}. PL_i and SLA_i are the partitioning factors for the leaf (g g^{-1}) and specific leaf area (m^2 g^{-1}), respectively, differing with development stages and genotypes. ΔL_{NL-5} was assumed to be equal to the daily increment of LAI when the ($n-5$)th leaf appeared ($n\geq5$). L_h in Eq. (7) is the LAI at heading and DVI_i is a developmental index to express the time scale, which is defined as the completed fraction of a given phase ranging in values from zero at heading to one at maturity. Field measurements show that the leaf area indices of *indica* and *japonica* at maturity are approximately 30% and 40% of that at heading. The constant a is, therefore, identified as 2.3 and 1.5 for *indica* and *japonica*, respectively.

Following McCree (1974), rice plant respiration was assumed to be in two parts, growth and maintenance. The growth respiration is related to photosynthesis and the maintenance respiration is a function of biomass and temperature.

$$\begin{aligned} R_i &= \mathrm{RG}_i + \mathrm{RM}_i \\ &= R_\mathrm{g}P_i + R_\mathrm{m}Q_{10}^{(T_i-25)/10}\left(\frac{\mathrm{BIM}_{i-1}}{0.58}\right) \end{aligned} \tag{8}$$

where R_i represents the daily amount of rice crop respiration (g CO_2 m^{-2} day^{-1}), a sum of growth respiration, RG_i, and maintenance respiration, RM_i. Q_{10} is a temperature coefficient for respiration, given a value of 2.0. BIM_{i-1} is the accumulated biomass (g m^{-2}) up to ($i-1$) days after transplanting. The coefficient of growth respiration, R_g, has a value of 0.30 (g CO_2 g CO_2^{-1}). For that of maintenance respiration, R_m, it is taken as 0.02 and 0.01 (g g^{-1} day^{-1}) before and after heading, respectively (Huang et al., 1990).

The contributions of preheading and postheading photosynthates to grain yield and the effect of temperature on grain filling were simulated by

$$\Delta\mathrm{GY}_i = \begin{cases} kT_i\left(k_l\frac{\mathrm{BIM}_h}{L} + k_2\Delta\mathrm{BIM}_i\right) \\ (\text{for } 1 \leq i \leq L) \\ kT_ik_2\Delta\mathrm{BIM}_i \\ (\text{for } L + 1 \leq i \leq \mathrm{HM}) \end{cases} \tag{9}$$

$$\mathrm{GY}_i = \mathrm{GY}_{i-1} + \Delta\mathrm{GY}_i \tag{10}$$

In Eq. (9), $\Delta\mathrm{GY}_i$ is the daily increment of grain yield (g m^{-2}) and kT_i represents the effect of temperature on grain filling. The terms $k_1\mathrm{BIM}_\mathrm{h}/L$ and $k_2\Delta\mathrm{BIM}_i$ represent the contribution of photosynthate produced preheading and postheading to grain yield formation, respectively. BIM_h is the biomass accumulation up to heading (g m^{-2}). Constant L is an assumed period during which a fraction of BIM_h was transferred to rice grain. L was set as 2/3(HM), and HM is the duration from heading to maturity in days. Coefficients k_1 and k_2, the respective preheading and postheading fractions of photosynthate transferred to grain, were determined by Eq. (11) and kT_i was computed by Eqs. (12) and (13) for different genotypes.

$$\begin{cases} k_1 = \alpha \mathrm{HI}(1+RW) \\ k_2 = (1-\alpha)\mathrm{HI}\dfrac{(1+RW)}{RW} \end{cases} \tag{11}$$

$$kT_i = \begin{cases} -8.97 + 0.799\mathrm{TD}_i - 0.0160\mathrm{TD}_i^2 \\ (\text{for } 17 < \mathrm{TD}_i < 25^\circ\mathrm{C}) \\ 1.00 \\ (\text{for } 25 \le \mathrm{TD}_i \le 29^\circ\mathrm{C}) \text{ for } \textit{indica} \text{ and} \\ -5.25 + 0.433\mathrm{TD}_i - 0.0075\mathrm{TD}_i^2 \\ (\text{for } 29 < \mathrm{TD}_i < 40^\circ\mathrm{C}) \text{ hybrid } \textit{indica} \end{cases} \tag{12}$$

$$kT_i = \begin{cases} -5.66 + 0.556\mathrm{TD}_i - 0.0116\mathrm{TD}_i^2 \\ (\text{for } 15 < \mathrm{TD}_i < 24^\circ\mathrm{C}) \\ 1.00 \\ (\text{for } 24 \le \mathrm{TD}_i \le 28^\circ\mathrm{C}) \text{ for } \textit{japonica} \\ -4.45 + 0.388\mathrm{TD}_i - 0.0069\mathrm{TD}_i^2 \\ (\text{for } 28 < \mathrm{TD}_i < 40^\circ\mathrm{C}) \end{cases} \tag{13}$$

Constant α in Eq. (11) is a fractional contribution of preheading accumulated photosynthate to grain yield, ranging from 0 to 0.40 under most conditions (Yoshida, 1981; Qi, 1986). HI is a crop harvest index and RW is a ratio of accumulated biomass from heading to maturity to that up to heading. The effect of temperature on grain filling, kT_i, is given a value between zero and one. When daytime temperature TD_i is optimum, kT_i equals one. Otherwise, kT_i is greater than zero and less than one. The optimum daytime temperature for rice grain filling is between 25°C and 29°C for *indica*, and between 24°C and 28°C for *japonica*. The lower temperature limit is between 15°C and 17°C, and the upper limit is between 38°C and 40°C (Qi, 1986).

2.2. Development

Crop development here is defined as the processes of crop phenology and leaf number increment. A ‘Rice clock model’ developed by the authors (Gao et al., 1992a) is used to simulate rice development.

The phenological development was modeled by

$$\int_{S_1}^{S_2} \mathrm{d}M = M = \exp(k)\sum_{i=1}^{n}\left(\frac{T_i - T_\mathrm{L}}{T_0 - T_\mathrm{L}}\right)^P \left(\frac{T_\mathrm{U} - T_i}{T_\mathrm{U} - T_0}\right)^Q \times \exp[G(D_i - D')] = 1 \tag{14}$$

where M represents the developmental progress for a given phase beginning at S_1 and ending at S_2 ($0 \le M \le 1$). T_U is the upper temperature limit for rice development, set at T_U =40°C. T_L is the lower temperature limit, taking the value of 10°C for *japonica*, 12°C and 13°C for *indica* and hybrid, respectively. T_0 is the optimum temperature for rice development, with the values of 28°C and 30°C for *japonica* and *indica* (Gao et al., 1987), respectively. T_i and D_i are the daily mean air temperature and day-length in hours within the development phase. D' is a critical day-length for rice development, taking D' =13 h. Constants K, P, Q and G are experimental parameters. For the developmental phase of sowing to emergence and that of heading to maturity, constants Q and G were evaluated as zero (Gao et al., 1992a). The accumulated total, M, is used as a criterion for the developmental phase when using Eq. (14) with a daily step. When the M value is integrated up to approximately 1.0, the number of days required to complete the phasic development, n, is determined.

The increment of leaf numbers on the main culm of a rice crop was simulated by

$$\mathrm{NL}_i = \exp(LK)\left[\sum_{j=1}^{i}\left(\frac{T_j}{T_0}\right)^{LA/LB}\right]^{LB} \quad \begin{cases} T_j = 0 & \text{for} T_j \le T_\mathrm{L} \\ T_j = T_0 & \text{for} T_j \ge T_0 \end{cases} \tag{15}$$

where NL_i represents the number of leaves and T_j is the daily mean air temperature. T_o and T_L are the optimum temperature and lower temperature limit for leaf development, which have the same values as that for phenological development. LK, LA, and LB are experimental coefficients (Gao et al., 1992a).

2.3. Model validation

The model for simulating rice development has already been validated by the authors (Gao et al., 1992a). Model predictions of biomass accumulation and grain yield formation were validated against measurements from the rice climatic–ecological experiments in 1985–1986 (Gao et al., 1992a, b) and the rice high-yielding cultivational experiments in 1988–1989 (Gao et al., 1992b).

The rice climatic–ecological experiments were conducted at 15 sites covering ten provinces (Sichuan, Shaanxi, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang, Fujiang and Shanghai) in the Yangtze River Valley and its adjacent rice cropping regions of China. A total of 20 varieties, representing six genotypes (hybrid *indica*, hybrid *indica*×*japonica*, medium *indica*, medium *japonica*, late *indica* and late *japonica*), were planted and two planting dates with an interval of 20–30 days apart were generally involved in the experiments. The rice high-yielding cultivational experiments were carried out at six sites (Nanjing, Baoying, Wujin, Dongtai, Huaiying and Suqian) in Jiangsu province, located between latitude 31°00′N and 34°30′N, and between longitude 117°30′E and 122°30′E. The experiments were conducted with four levels of nitrogen application ranging from 0.0 to 195 kg N/ha in the entire growing season, and three levels of transplanting densities ranging from 70×10^4 to 165×10^4 per hectare. Details of these two experiments have been described by several authors (Gao et al., 1992a, b; Huang et al., 1990, 1996).

Simulated rice above-ground biomass was in good agreement with the observed data (Fig. 1), resulting in a r^2 of 0.952 ($P<0.001$). The observed data sets for the medium *indica* of N.J.3736 (cross points) were from the rice climatic–ecological experiments at four locations of Jiangsu province. Those for the hybrid *indica* of S.U.63 (circle points) were from the rice high-yielding cultivational experiments at Nanjing, Jiangsu province. Simulated grain yields for four different genotypes (hybrid *indica*, medium *indica*, medium *japonica* and late *japonica*) were in general agreement with observed data from the rice climatic–ecological experiments distributed among the above mentioned 15 sites. The regression of simulated against observed (Fig. 2) yields a r^2 of 0.638 ($P<0.001$).

3. Optimal growing season

To match local cropping systems, the earliest possible sowing date of rice should be 30–40 days before harvesting the previous crops, providing a typical seedling age of equal length. The latest harvesting date of rice needs to be about one week earlier than the sowing date of the following crops, in consideration of time requirement for harvesting rice. The optimal growing season of rice crops is restricted within these two extremes. A conceptual diagram of the cropping season is shown in Fig. 3.

Beginning at the earliest possible sowing date (Fig. 3), the phenological development was simulated in the order of sowing, emergence, heading and maturity with an assumed sowing date interval of 5 days. Corresponding biomass and grain yield production was modeled from transplanting to maturity. Four rice genotypes (hybrid *indica*, medium *indica*, medium *japonica* and late *japonica*) were selected to determine their optimal growing seasons at a total of 23 representative sites in the Yangtze River Valley and its adjacent rice growing regions, located between latitudes 24°30′N and 35°00′N, and between longi-

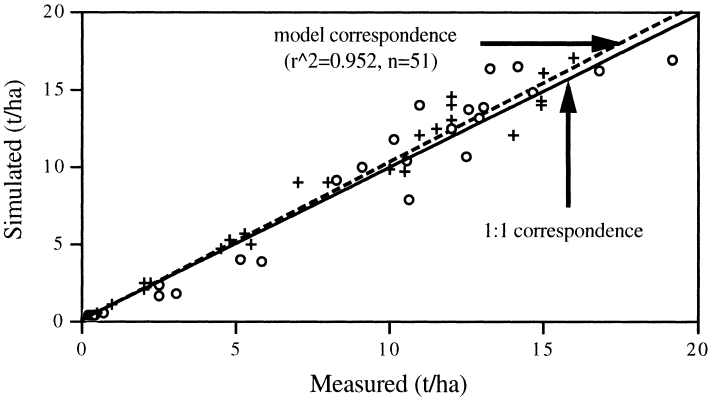

Fig. 1. Comparison of simulated with measured rice above-ground biomass for a medium *indica* of N.J.3736 (crosses) and a hybrid *indica* of S.U.63 (circles). Model correspondence is the regression line of simulated vs. measured biomass.

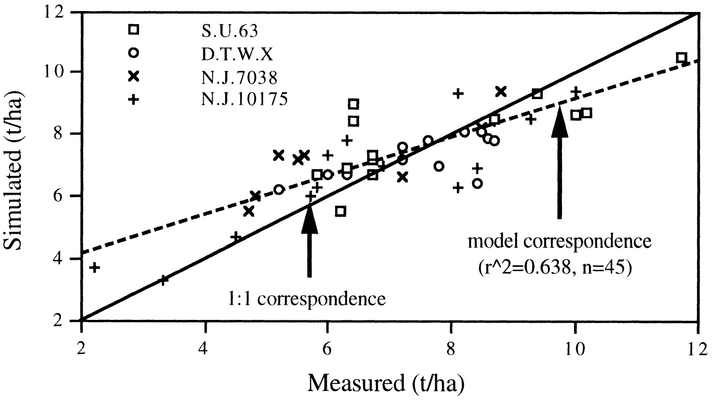

Fig. 2. Comparison of simulated with measured grain yield for four rice varieties of S.U.63 (hybrid *indica*), D.T.W.X. (medium *indica*), N.J.7038 (medium *japonica*) and N.J.10175 (late *japonica*). Model correspondence is the regression line of simulated vs. measured grain yield.

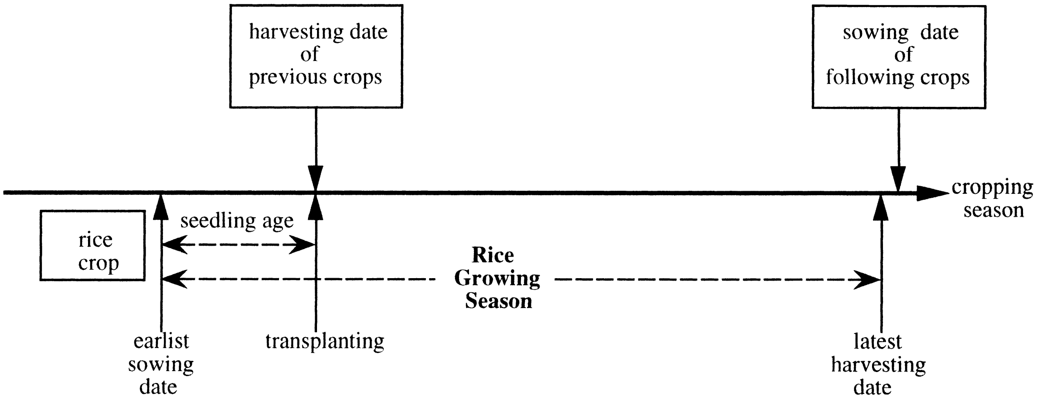

Fig. 3. A conceptual diagram of cropping season.

tudes 103°50′E and 122°30′E (Gao et al., 1992a). Approximately 70% of the total rice cropping area in China is distributed in this region. Tables 1 and 2 present the model parameters for simulating leaf area extension, biomass and grain yield production, respectively. The model parameters for simulating the phenological development of different rice genotypes (Gao et al., 1992a) is shown in Table 3. Climatic inputs of daily solar radiation and temperature in a normal harvest year come from local weather service

Table 1
Partitioning fraction of photosynthate to leaf tissue (PL) and specific leaf

Phenological stage	PL (g g^{-1})		SLA (m^2 g^{-1})	
	Indica	*Japonica*	*Indica*	*Japonica*
Tillering	0.38	0.38	0.028	0.025
Elongation	0.35	0.35	0.026	0.023
Booting	0.30	0.30	0.025	0.022
Heading	0.00	0.00	0.024	0.021

Table 2
Experimental parameters for simulating photosynthesis and grain yield formation

Phenological phase	Parameters	Varieties S.U.63 Hybrid i.[a]	 D.T.W.X. Medium i.	 N.J.7038 Medium j.[b]	 N.J.10175 Late j.
Pre-heading	*A*	9.6	5.2	7.2	4.3
Post-heading	*A*	7.2	5.7	4.5	4.8
Pre-heading	*B*	23.5	17.8	22.6	14.4
Post-heading	*B*	16.0	14.6	12.9	11.7
Pre-heading	*k*	0.39	0.41	0.41	0.45
Post-heading	*k*	0.69	0.70	0.70	0.67
Pre-heading	*f*	0.06	0.06	0.06	0.06
Post-heading	*f*	0.10	0.10	0.09	0.09
	HI	0.56	0.53	0.54	0.54
	RW	0.52	0.52	0.55	0.55

[a] *Oryza indica*.
[b] *Oryza japonica*.

Table 3
Experimental parameters for simulating phenological development of different rice genotypes (Gao et al., 1992a)

Developmental Phase	Parameters	Varieties S.U.63 Hybrid[a]	 D.T.W.X. Medium i.	 N.J.7038 Medium i.[b]	 N.J.10175 Late j.
sowing-emergence	*K*	−0.60	−0.83	−0.70	−0.65
	P	0.40	0.45	0.56	0.80
emergence-heading	*K*	−4.39	−4.37	−4.08	−4.24
	P	1.27	1.12	2.76	1.71
	Q	0.78	0.42	1.63	1.00
	G	0.00	0.00	−0.29	−0.36
heading-maturity	*K*	−3.56	−3.50	−3.33	−3.58
	P	0.23	0.27	0.88	0.34

[a] *Oryza indica*.
[b] *Oryza japonica*.

centers. Outputs of the simulation include phenological stages, biomass and grain yield under different assumed sowing dates.

As an example, Fig. 4 presents the simulated grain yields of a hybrid *indica* S.U.63 at assumed growing seasons. Obviously, the optimal growing season at Nanjing for this kind of variety lies in the period between 20 May and the beginning of October. For increased flexibility, rice crops of S.U.63 planted between 10 and 30 May will be expected to produce higher grain yield than that in the other seasons (Fig. 4). Following these sowing dates, filling and ripening occur in the period between mid August and the first 10 days of October. During this period, high solar radiation is accompanied with moderate temperature in this area, which enhances net photosynthetic accumulation and eventually results in a high grain yield.

Table 4 presents the simulated optimal growing seasons and the relevant grain yields for four rice

Table 4
Optimal growing season and predicted grain yield for four rice genotypes in the Yangtze River Valley and its adjacent area, China

Rice growing region	Location	Varieties											
		S.U.63 Hybrid i.[a]			D.T.W.X. Medium i.			N.J.7038 Medium j.[b]			N.J.10175 Late		
		S[c] (M/D)	H[d] (M/D)	GY[e] (t/ha)	S (M/D)	H (M/D)	GY (t/ha)	S (M/D)	H (M/D)	GY (t/ha)	S (M/D)	H (M/D)	GY (t/ha)
Huabei plain	Xian 34°18′N 108°56′E	4/10	8/12	11.25	4/20	8/15	8.92	4/20	8/17	9.57	4/20	8/25	8.56
	Xuzhou 34°17′N 117°18′E	4/20	8/13	10.53	5/10	8/15	8.61	5/10	8/15	9.00	5/05	8/25	8.31
Middle-lower region of the Yangtze River Valley	Nanjing 32°00′N 118°48′E	5/20	8/20	10.05	5/10	8/18	8.31	4/30	8/09	8.41	4/30	8/19	8.10
	Wuhan 30°38′N 114°04′E	5/10	8/09	10.39	4/25	8/06	8.62	5/10	8/08	8.58	4/25	8/11	8.43
	Changsha 28°12′N 113°04′E	4/30	7/30	9.91	4/20	8/01	8.19	5/20	8/06	7.92	4/30	8/07	7.98
Southwest China	Congqing 29°35′N 106°28′E	4/10	7/29	10.03	4/10	7/30	8.20	5/15	8/08	8.04	4/20	8/06	8.01
	Chengdou 30°40′N 104°01′E	4/10	8/07	9.78	4/10	8/09	8.04	4/10	8/07	8.10	4/10	8/12	7.90
	Guiyang 26°35′N 106°43′E	4/20	8/19	10.15	4/20	8/23	8.19	4/20	8/14	8.46	4/20	8/16	7.96

[a] *Oryza indica.*
[b] *Oryza japonica.*
[c] Sowing.
[d] Heading.
[e] Grain yield.

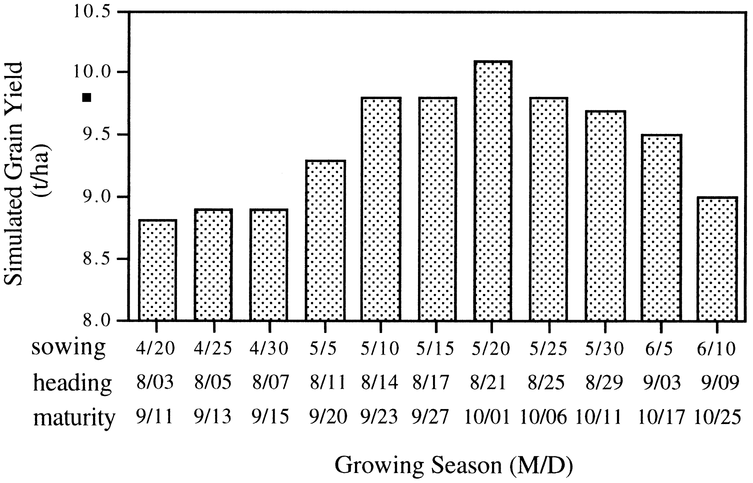

Fig. 4. Simulated grain yields under assumed growing seasons, Nanjing, China (32°00′N, 118°48′E), Var. S.U. 63.

genotypes in the Yangtze River Valley and its adjacent rice growing regions. The optimal sowing dates were determined to be between 10 April and 20 May and the corresponding heading dates occur in the period from the end of July to the end of August. The simulated grain yields vary from a value of 7.90 (late *japonica* N.J.10175, Chengdou, Southwest China) to 11.25 t/ha (hybrid *indica* S.U.63, Xian, Huabei Plain). The results from different varieties show a tendency of higher grain yield in northern China than in southern China. A recognized reason is that the growth duration in northern China is generally longer than that in southern China (Table 4) and an increase in total solar radiation from south to north can also be found from the climatic inputs, both of which make great contributions to rice production.

For most rice cropping regions in the area studied, the precipitation during rice growing season is plentiful (Domrös and Peng, 1988) and the paddy soils are suitable for rice growth (Li and Sun, 1990). It is, therefore, possible to acquire the predicted grain yields shown in Table 4 when nutrients are available in supply. Available information from local agricultural research and extension stations in Hanzhong, Xuzhou, Xinhua, Santai and Jianglin show that the observed grain yields under optimal planting dates for genotypes of hybrid *indica* and traditional *indica* were very close to the predicted values (Fig. 5(a,b)) while

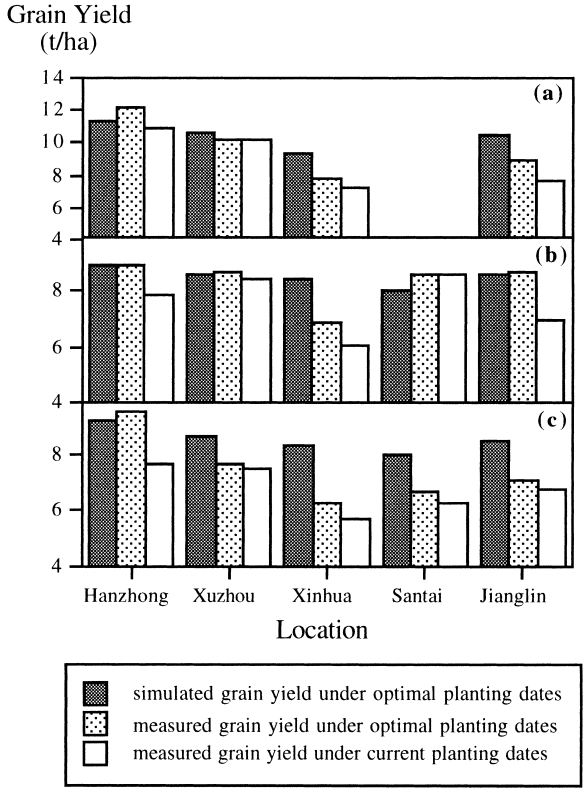

Fig. 5. Comparison between grain yields under simulated optimal and current planting dates for hybrid *indica* (a), traditional *indica* (b) and traditional *japonica* (c).

Table 5
Comparison between grain yields under simulated optimal and current planting dates for three rice genotypes

Location (latitude, longitude)			Grain yield (t/ha)								
	Planting date (M/D)		Hybrid i.[a]			Traditional i.			Traditional j.[b]		
	Po[c]	Pc[d]	Yso[e]	Ymo[f]	Yc[g]	Yso	Ymo	Yc	Yso	Ymo	Yc
Hanzhong (34°00′N, 106°30′E)	4/10 – 4/30	4/20 – 5/10	11.25	12.11	10.91	8.92	8.90	7.90	9.20	9.56	7.69
Xuzhou (34°17′N, 117°18′E)	4/20 – 5/10	4/20 – 5/15	10.53	10.21	10.13	8.61	8.70	8.41	8.66	7.68	7.51
Xinhua (33°47′N, 114°31′E)	4/30 – 5/20	5/10 – 5/30	9.32	7.81	7.30	8.45	6.90	6.07	8.35	6.30	5.68
Santai (31°10′N, 105°00′E)	4/05 – 4/20	4/15 – 5/05				8.04	8.59	8.62	8.00	6.72	6.27
Jianglin (30°24′N, 112°05′E)	4/25 – 5/15	late than 5/25	10.39	8.95	7.67	8.62	8.69	6.94	8.51	7.08	6.74
Average of grain yield			10.37	9.77	9.00	8.53	8.36	7.59	8.54	7.47	6.78
Average of (Yso/Ymo)[h] (%)			106			102			115		
Average of (Yso/Yc) (%)			115			112			127		
Average of (Ymo/Yc) (%)			109			110			110		

[a] *Oryza indica.*
[b] *Oryza japonica.*
[c] Simulated optimal planting dates.
[d] Current planting dates.
[e] Simulated grain yield under optimal planting dates.
[f] Measured grain yield under optimal planting dates.
[g] Measured grain yield under current planting dates.
[h] Calculated with $\frac{1}{n}\sum\left(\frac{\mathrm{Yso}}{\mathrm{Ymo}}\times 100\right)$; n is number of locations. Same calculations as for the averages of (Yso/Yc) and (Ymo/Yc).

those for genotype of traditional *japonica* were in general lower than the predicted yields (Fig. 5(c)). The average predicted grain yields from these locations were 10.37, 8.53 and 8.54 t/ha for hybrid *indica*, traditional *indica* and traditional *japonica*, respectively. Observations result in the average value of 9.77, 8.36 and 7.47 t/ha, respectively (Table 5).

Observations from the above-mentioned locations show that rice grain yields under current planting dates were generally lower than those under the optimal planting dates (Fig. 5), which is recognized as a result of late planting (Table 5). The observed grain yields from Jianglin (Table 5), where the current planting dates are much later than the optimal, were approximately 13% and 22% lower than the yields observed and predicted with the optimal planting dates. Compared with this, the observed grain yields from Xuzhou (Table 5), where the current planting dates are close to the optimal, were only about 2% and 6% lower than yields observed and predicted with the optimal planting dates.

An average ratio of grain yields under the optimal planting dates to those under current planting dates was calculated to evaluate the potential increase in rice production. Calculations indicate that an average increase of 10% in rice grain yield is likely when rice plants are planted in an optimal period, approximately 10 days earlier than current planting dates (Table 5). In this crop calendar, alternative crops with a short-duration should be chosen to plant in the previous cropping season for the preparation of land for rice seedlings.

4. Summary and conclusion

In this paper, we presented a model for simulating rice growth and development. The model was then employed to simulate optimal growing seasons for four rice genotypes (hybrid *indica*, medium *indica*, medium *japonica* and late *japonica*) in the major rice-growing region of China.

With a focus on the dependence of rice growth and development upon climatic conditions, simulation of rice photosynthetic production was driven by daily climatic variables including solar radiation, maximum and minimum temperature, and varietal parameters of photosynthetic characteristics, leaf area, partitioning fraction of photosynthate to leaf tissue, and specific leaf area for different genotypes. The contributions of photosynthate produced before and after heading to grain yield formation and the effect of temperature on grain filling were incorporated into the growth model. Plant phenological development was simulated as influenced by daily temperature and day-length. Model predictions of biomass accumulation and grain yield formation were validated against field measurements and good agreement between simulated and observed data sets was obtained.

By applying the developed model to the Yangtze River Valley and its adjacent area, covering approximately 70% of the total rice cropping area in China, the optimal growing seasons and their relevant grain yields for the four rice genotypes were determined. Simulations showed that the optimal sowing dates are between 10 April and 20 May depending on location and the corresponding heading dates occur in the period from the end of July in the southwest region to the end of August in the Huabei plain of China. The simulated grain yields under these optimal growing seasons vary from a value of 7.90 to 11.25 t/ha.

Observations from various rice growing regions indicated that grain yields under optimal planting period were higher than those outside the optimal. Calculations suggested that an average increase of 10% in grain yield is possible when rice plants are planted in the simulated optimal period, approximately 10 days earlier than current planting dates. In this crop calendar, crops with an alternative short-duration should be chosen to plant in the previous cropping season for the preparation of land for rice seedlings.

The development of crop models is usually aimed at understanding the crop-environment interactions relevant to crop growth and development. This study showed that application of crop modeling techniques in agricultural management might have great potential with respect to improving agricultural productivity under local natural conditions. To extend this kind of research, a model that takes not only varietal and climatic parameters but also soil and nutrient uptake into account would be more useful.

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