Simulation and Validation of Rice Potential Growth Process in Zhejiang Province of China by Utilizing WOFOST Model

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Abstract: A crop growth model of WOFOST was calibrated and validated through rice field experiments from 2001 to 2004 in Jinhua and Hangzhou, Zhejiang Province. For late rice variety Xiushui 11 and hybrid Xieyou 46, the model was calibrated to obtain parameter values using the experimental data of years 2001 and 2002, then the parameters were validated by the data obtained during 2003. For single hybrid rice Liangyoupeijiu, the data recorded in 2004 and 2003 were used for calibration and validation, respectively. The main focus of the study was as follows: the WOFOST model is good in simulating rice potential growth in Zhejiang and can be used to analyze the process of rice growth and yield potential. The potential yield obtained from the WOFOST model was about 8100 kg/ ha for late rice and 9300 kg/ ha for single rice. The current average yield in Jinhua is only about 78% (late rice) and 70% (single rice) of their potential yield. The results of the simulation also showed that the current practice of management at the middle and late growth stages of rice should be reexamined and improved to reach optimal rice growth.

Key words: crop growth model; rice; yield; crop growth process; simulation; calibration

Since the pioneering work in the 1960s, substantial progress has been made in crop growth simulation both in developing and applying models. Crop growth simulation integrates the knowledge of computer science, phytophysiology, agroecology, agrometeorology, soil science, agronomy and systems, combines the plant and environmental factors, and describes quantitatively the dynamic relation between crop growth, development, yield formation and environmental techniques [1].

WOFOST (World Food Studies Crop Growth Model) model originated in the framework of interdisciplinary studies on world food security and on the potential world food production by the Center for World Food Studies in cooperation with the Wageningen Agricultural University [2]. It was updated from version 3.1 to version 7.1 and the successive WOFOST versions have been used in many areas of foreign countries, however, in China it was only validated in North China Plain using winter wheat [3].

Rice stands amongst the most important crop of Zhejiang Province. About 70% of food crop sowing area and 83% of total food crop yield in Zhejiang Province is paddy and 95% of Zhejiang dwellers live on rice. However, there are few crop simulation studies on analyzing rice potential growth process in Zhejiang.

The inner structure of rice planting in Zhejiang has been changed greatly in recent years [4]. The sowing area of early rice, single rice and late rice accounted for 37.3%, 20.4% and 42.3% respectively of the total rice planting area in 1998. However, these figures changed to 18.8%, 58.1% and 23.1% in 2002. Now the single rice is the main part of rice production.

The objective of current study is to simulate the growth process and yield potential of late and single rice using WOFOST. A suit of parameters adapting to Zhejiang region were obtained and validated using the data of rice field experiments.

MATERIALS AND METHODS

Experimental design

Field experiments were conducted at Shimen State Farm, Jinhua (29°7’ N, 119°39’ E) of Zhejiang

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Province. Rice variety Xiushui 11 and hybrid rice Xieyou 46 were grown in 30 m^2 plot during late season in 2001-2003, while the hybrid rice Liangyoupeijiu was only planted in single season of 2003. Two Nitrogen (N) treatments (0 and 180 kg N/ha) were used in randomized complete block design with four replicates. N fertilizer was applied with 40% as basal dose, 30% at early tillering and remaining 30% at panicle initiation. Moreover, a basal dose of 23 kg/ha of phosphorus (P) and 100 kg/ha of potassium (K) fertilizers were also applied. On the other hand, the control plots only received the full dose of P and K without any N. The plant-to-plant space was kept 20 cm × 20 cm. The plants were sown, transplanted and harvested in the following order: a) For Xiushui 11, sowing, transplanting, and harvesting were conducted on 25 June, 20 July, and 5 November, respectively; b) For Xieyou 46, sowing, transplanting and harvesting were on 15 June, 20 July, and 25 October, respectively; c) For Liangyoupeijiu, sowing, transplanting and harvesting were on 25 May, 25 June, and 10 October, respectively.

Trial for Liangyoupeijiu was performed in Huajiachi Campus of Zhejiang University (30°14’ N, 120°10’ E) in 2004 on 16 m^2 plot size with three replications in a complete random design. The fertilizer treatments were the same as in the experiments of 2003 in Jinhua. The plant-to-plant space was 20 cm × 20 cm. The sowing, transplanting and harvesting was done on 20 May, 17 June and 14 October, respectively.

The plots were kept flooded throughout the experiment, while the diseases, weeds and other pests were intensively controlled to avoid yield losses.

Plant sampling and measurements

Five hills of rice plants at each plot were collected and sampled into leaf blades, culms plus sheaths and grains at 7 to 10 d intervals after transplanting. The samples were oven-dried at 70℃ till constant weight. A total of 125 hills of the rice plants at each plot were sampled at maturity to measure yield and yield components. In 2004, the leaf area of Liangyoupeijiu was calculated by a special computer software after scanning. In 2003, the leaf area of Liangyoupeijiu was calibrated by multiplying the leaf dry weight with a conversion coefficient obtained in 2004 at different growth stages. The leaf area of Xiushui 11 and Xieyou 46 was calibrated in the same way by using the conversion coefficients of Zheng et al [5].

Weather data

The weather information for WOFOST simulation includes daily maximum temperature, daily minimum temperature, daily global irradiation, precipitation, and mean wind speed at 2 m above ground. Weather information from Jinhua Weather Station and Hangzhou Weather Station were used in this study.

Model description

WOFOST is a dynamic, explanatory model [6]. It simulates annual crop growth with time steps of one day. The simulation is based on ecophysiological processes, mainly including phenological development, CO_2-assimilation, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation.

Three hierarchical levels of crop growth can be distinguished in WOFOST. The first level is the potential production situation, where nutrients and water are in ample supply. Hence, growth is determined by irradiation, temperature and plant characteristics only. The second level is the water-limited production situation, where nutrient supply is sufficient, but low water availability may lead to growth reduction. The third level is the nutrient-limited production situation. However, a yield reduction through biotic factors such as weeds and pests is not considered yet in current version [6]. Only the running of WOFOST under the first level was considered in this paper.

In the potential production situation WOFOST uses a detailed approach to describe the light interception of the canopy, considering site-specific atmospheric transmissivity, incoming diffuse and direct light, reflection and scattering with the canopy as well as light absorption [7]. Given Equation (1) indicates the implemented approach, with which WOFOST represents light interception for each layer from the top of the canopy downwards.

$$R_{\mathrm{P},I} = R_{\mathrm{P}}(1-\rho)e^{(-k\,L)} \quad (1)$$

Where $R_{P,I}$ is the intercepted photosynthetic active radiation [J/(m^2 • s)] at the I^{th} layer, R_P is the photosynthetic active radiation [J/(m^2 • s)] at the top of the canopy, ρ is the reflection-coefficient of the canopy, k is the extinction coefficient and L is the leaf area index (LAI, m^2/m^2). The extinction coefficient is radiation (direct and diffuse) specific.

The instantaneous gross assimilation in WOFOST is estimated through an assimilation-light response function of individual leaves:

$$A = A_M\,[1 - e^{(-\varepsilon R_{P,I}/A_M)}] \qquad (2)$$

Where A is the gross assimilation rate [kg/(ha • h)], A_M is the gross assimilation rate at light saturation [kg/(ha • h)] and ε is the initial light use efficiency[(kg • ha^{-1} h^{-1})/(J • m^{-2} s^{-1})].

Developmental phase is calculated by temperature sum [Equation (3)] or photoperiod [Equations (4) and (5)].

$$D = \frac{\int T_e}{T_{req}} \qquad (3)$$

$$F_{pr} = \frac{P - P_c}{P_o - P_c}\ ;\ 0 \leqslant F_{pr} \leqslant 1 \qquad (4)$$

$$D = F_{pr} \cdot \frac{\int T_e}{T_{req}} \qquad (5)$$

In Equation (3), D is developmental stage, T_e is daily effective temperature, T_{req} is temperature sum from emergence to flowering and temperature sum from flowering to maturity. While in Equation (4), P is a photoperiod, P_o is a optimum photoperiod, P_c is a critical photoperiod and F_{pr} is a photoperiod reduction factor.

A fraction of carbohydrates produced by plant are used to provide energy and biomass, while the remaining is converted into structural matter. During this conversion process, some of the weight lost due to the respiration. The dry matter produced is then partitioned amongst the various plant organs such as roots, leaves, culms and storage organs, by using partitioning factors that are a function of the phonological developmental stage of the crop [8]. Leaf mass is subdivided into age classes. During the development of the crop a fraction of living biomass dies due to senescence. The dry weights of the plant organs are obtained by integrating their growth rate over time. See Fig. 1.

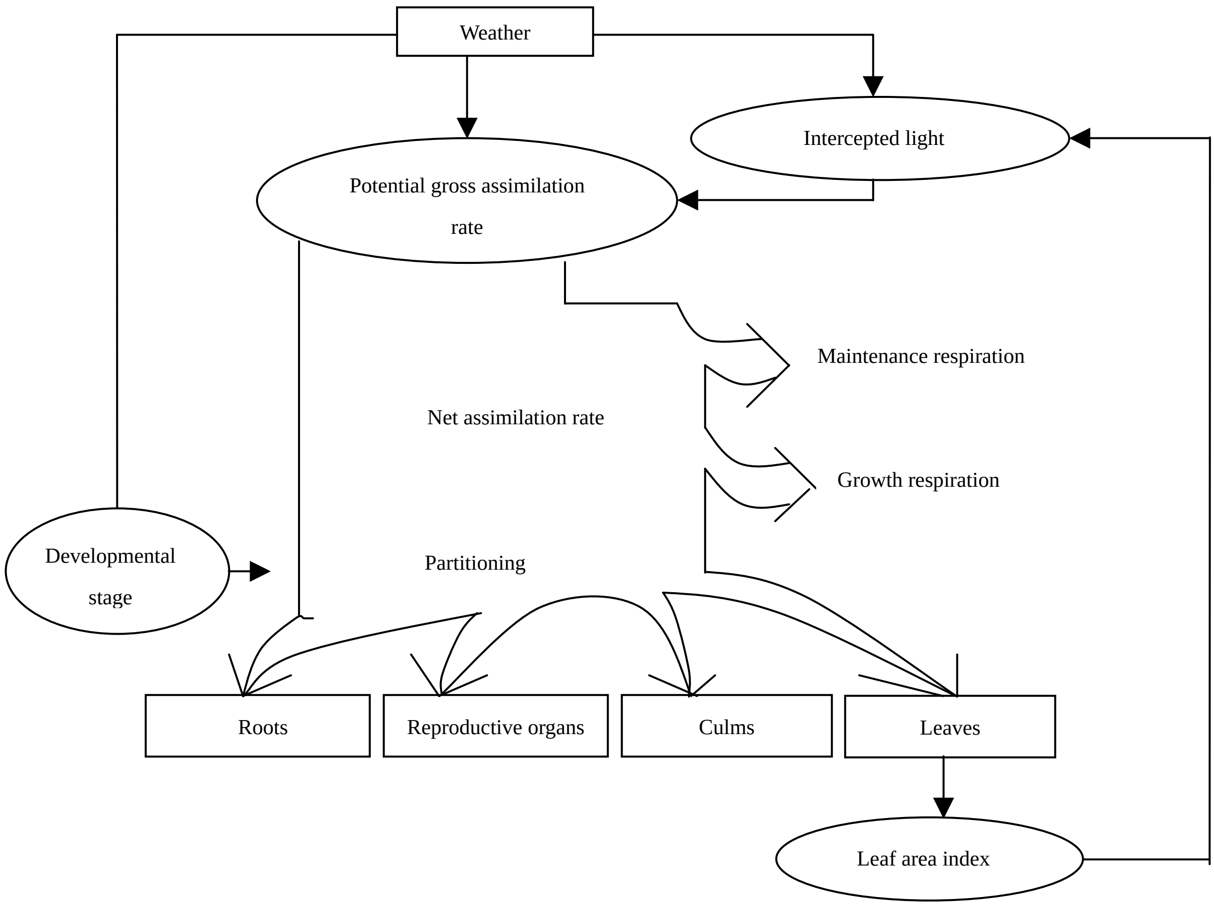

Fig. 1. Simplified general structure of a dynamic, explanatory crop growth model at potential level of WOFOST.

RESULTS

WOFOST was programmed by Fortran Simulation Translator (FST). The key developmental stages of rice plants are emergence (0), flowering (1), and physiological maturity (2). Model can run under Windows circumstance.

Revised parameters

In this study the crop data were obtained by field trials and agronomic literatures [9-14]. The characteristic parameters of different rice varieties were measured carefully during field trials. The experimental data of 2001 to 2002 (Xiushui 11 and Xieyou 46) and data of 2004 (Liangyoupeijiu) were used to calibrate the parameters. The revised parameters and functions were listed in Table 1 and Table 2. TSUM1 represents accumulative temperature sum from emergence to flowering, TSUM2 represents accumulative temperature sum from flowering to maturity, DVSI represents developmental stage starting simulation (after transplanting), TDWI represents total dry weight at initialization, LAIEM represents leaf area index at transplanting, RGRLAI represents maximum relative increase in LAI (Table 1). SLATB, FRTB, FLTB, FSTB, AMAXTB, KDIFTB and EFFTB (Table 2) are specific leaf area, dry root weight, dry leaf weight, dry culm weight, maximum leaf CO_2 assimilation rate, extinction coefficient for diffuse visible light as a function of developmental stage and light-use efficiency of single leaf as a function of daily mean temperature, respectively.

After putting the revised parameters into the model and running model, results were output. Then the simulated results and measured values were compared. The data obtained during 2003 were used to validate the model for all three cultivars.

The growth process of rice

The simulated values of leaf area index, dry culm weight, storage organs (WSO) and total above ground dry matter (TAGP) were compared with the measured values, respectively. It could be seen from Fig. 2 that all of the simulated results were higher than the measured values. However, the changed patterns of simulated results were similar with the measured values. It indicated that WOFOST could simulate the dynamics of rice growth; moreover, the simulated potential yields were near to the high yield recorded in the recent years. Thus, it could be concluded that the use of WOFOST is a suitable approach in the study of rice production in Jinhua area of Zhejiang.

A gap has been noted between the simulated results and the measured values, indicating that the current production status did not reach the optimum conditions. The great potential has been found to increase rice yield in this area. Despites all the mentioned potentials, some limitation exists during the current field management, such as unbalanced nutrient supply, insufficient supply of nitrogen at the middle and late rice growth stages, etc [13].

Rice yield

The potential yield obtained from WOFOST is about 8000 kg/ha for Xiushui 11, 8100 kg/ha for Xieyou 46 and 9300 kg/ha for Liangyoupeijiu, which is close to the highest yield recorded locally. However, the statistical data from Jinhua Agricultural Bureau indicated that the average yield is about 6300 kg/ha for late rice and 6500 kg/ha for single rice from 1998 to 2002 in Jinhua region where Xieyou 46 and Liangyoupeijiu are the main varieties. The current average yield is only about 78% (late rice) and 70%

Table 1. Revised parameters.

Rice variety or hybrid combination	TSUM1 (℃ • d)	TSUM2 (℃ • d)	DVSI	TDWI (kg/ ha)	LAIT	RGRLAI (ha/ha • ℃ • d)
Xiushui 11	1730	530	0.38	100	0.01	0.0080
Xieyou 46	1640	480	0.38	100	0.01	0.0070
Liangyoupeijiu	1800	750	0.23	40	0.01	0.0070

TSUM1, Temperature sum from emergence to flowering; TSUM2, Temperature sum from flowering to maturity; DVSI, Developmental stage at simulation initialization; TDWI, Total dry weight at initialization; LAIT, LAI at transplanting; RGRLAI, Maximum relative increase in LAI.

Table 2. Revised functions.

Function	Value
SLATB	Xiushui 11: 0.00, 0.0030, 0.61, 0.0030, 0.80, 0.0029, 1.00, 0.0025, 1.55, 0.0025, 2.00, 0.0018
	Xieyou 46: 0.00, 0.0037, 0.43, 0.0037, 0.74, 0.0030, 0.84, 0.0030, 1.00, 0.0029, 2.10, 0.0021
	Liangyoupeijiu: 0.00, 0.0075, 0.18, 0.0075, 0.65, 0.0024, 1.00, 0.0024, 1.55, 0.0023, 2.00， 0.0019
FRTB	Xiushui 11: 0.00, 0.45, 0.43, 0.45, 0.80, 0.35, 0.85, 0.00, 1.00, 0.00, 2.00, 0.00
	Xieyou 46: 0.00, 0.50, 0.43, 0.35, 0.65, 0.50, 0.80, 0.25, 0.85, 0.05, 0.99, 0.05, 1.00, 0.00, 2.00, 0.00
	Liangyoupeijiu: 0.00, 0.40, 0.25, 0.20, 0.40, 0.20, 0.50, 0.50, 0.70, 0.40, 0.72, 0.00, 1.00, 0.00, 2.00, 0.00
FLTB	Xiushui 11: 0.00, 0.65, 0.50, 0.62, 0.60, 0.57, 0.70, 0.57, 0.80, 0.38, 1.00,0.00, 2.10, 0.00
	Xieyou 46: 0.00, 0.65, 0.50, 0.62, 0.60, 0.57, 0.70, 0.57,0.80, 0.40, 0.85, 0.13, 1.00, 0.00, 2.10, 0.00
	Liangyoupeijiu: 0.00, 0.65, 0.31, 0.65, 0.53, 0.57, 0.80, 0.35, 0.94, 0.20, 1.00, 0.15, 1.13, 0.00, 2.00, 0.00
FSTB	Xiushui 11: 0.00, 0.35, 0.50, 0.38, 0.60, 0.43, 0.70, 0.43, 0.80, 0.62, 1.00, 0.40, 1.20, 0.00, 2.10, 0.00
	Xieyou 46: 0.00, 0.35, 0.50, 0.38, 0.60, 0.43, 0.80, 0.60, 0.85, 0.35, 1.00, 0.30, 1.20, 0.00, 2.10, 0.00
	Liangyoupeijiu: 0.00, 0.35, 0.53, 0.43, 0.80, 0.65, 0.94, 0.50, 1.00, 0.15, 1.13, 0.00, 1.20, 0.00, 2.00, 0.00
AMAXTB	Xiushui 11: 0.00, 40, 1.00, 40, 1.90, 40, 2.00, 40
	Xieyou 46: 0.00, 40, 0.75, 50, 0.85, 50,1.00, 35, 1.90, 35, 2.00, 35
	Liangyoupeijiu: 0.00, 50, 0.20, 45, 0.35, 40, 0.70, 40, 0.80, 50, 2.00, 50
KDIFTB	Xiushui 11: 0.00, 0.40, 0.65, 0.40, 1.00, 0.60, 2.00, 0.60
	Xieyou 46: 0.00, 0.40, 0.65, 0.40, 1.00, 0.60, 2.00, 0.60
	Liangyoupeijiu: 0.00, 0.40, 0.65, 0.40, 1.00, 0.60, 2.00, 0.60
EFFTB	Xiushui 11: 10, 0.54, 40, 0.36
	Xieyou 46: 10, 0.54, 40, 0.36
	Liangyoupeijiu: 10, 0.54, 40, 0.36

SLATB, Specific leaf area as a function of developmental stages; FRTB, Fraction of total dry matter to roots as a function of developmental stages; FLTB, Fraction of aboveground dry matter to leaves as a function of developmental stages; FSTB, Fraction of aboveground dry matter to culms as a function of developmental stages; AMAXTB, Maximum leaf CO_2 assimilation rate as a function of developmental stages; KDIFTB, Extinction coefficient for diffuse visible light as a functional of developmental stages; EFFTB, Light use efficiency for single leaf as a function of daily mean temperature.

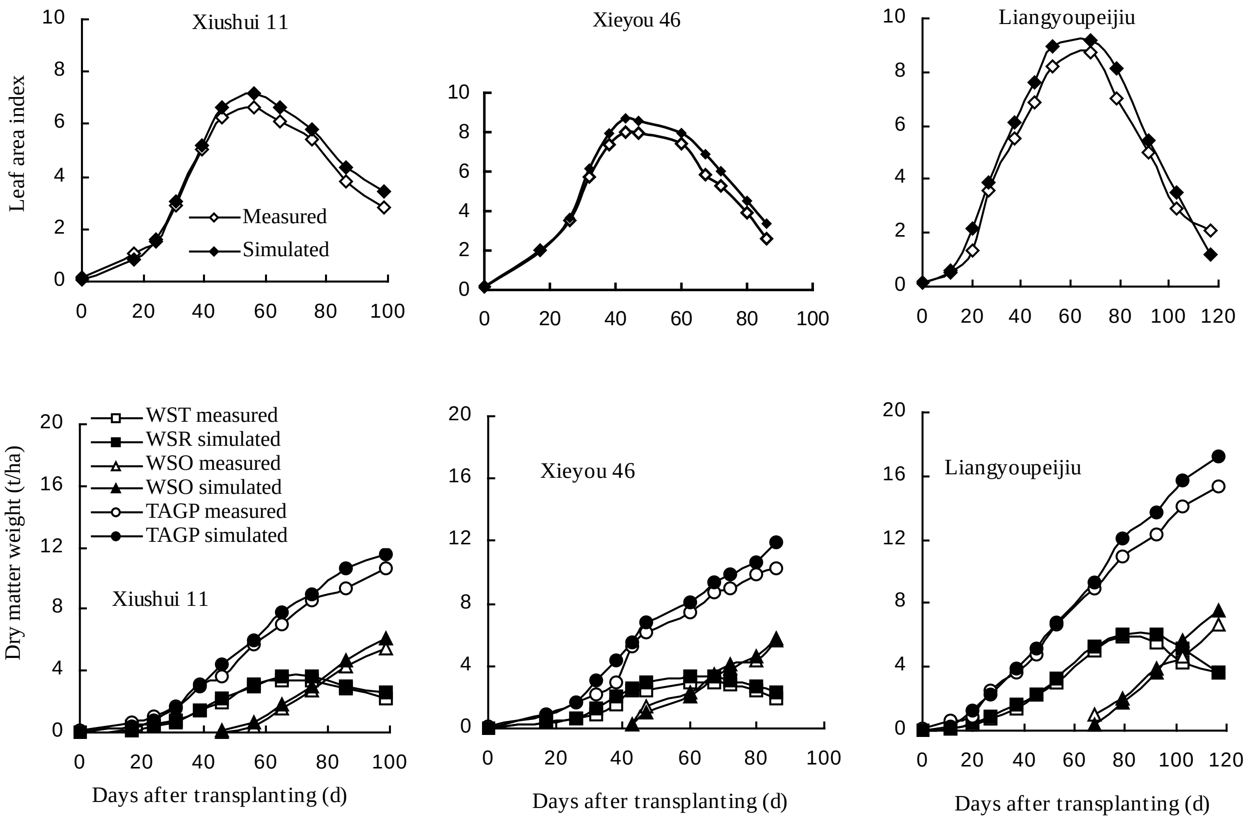

Fig. 2. Comparison of simulated results and measured values for rice (2003).

WST, WSO and TAGP are dry weight of living culms, living storage organs and total above-ground production, respectively.

(single rice) of their potential yields; the gap between the simulated results and the measured values is large. Thus current rice cropping practice should be reexamined to optimize the management of water and fertilizer inputs.

DISCUSSION

WOFOST model is helpful in simulating rice potential growth, and it is useful in studying rice production in Zhejiang, China.

The simulated results indicate that the current average yield of late rice and single rice in Jinhua is only about 78% (late rice) and 70% (single rice) of their potential yields. Therefore, a great potential is found to increase rice yield through better crop management.

The difference between the simulated results and the measured values revealed that some unfavorable practice existed in the current crop management. While the difference become larger at the middle and late stages of rice growth due to insufficient nitrogen supply might have occurred [14].

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