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Potential production simulation and optimal nutrient management of two hybrid rice varieties in Jinhua, Zhejiang Province, China*

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Abstract: Potential growth of two widely-grown hybrid rice varieties in the Jinhua district of Zhejiang Province, Shanyou63 for mid-rice and Xieyou46 for late rice, was simulated using a crop growth model of WOFOST. Parameters of the rice growth in WOFOST were calibrated through field experiments from 1999 to 2002 in Jinhua. The potential yield simulated with WOFOST was about 12 t/ha for Shanyou63 and 10 t/ha for Xieyou46, which are in good agreement with the highest recorded yield obtained in this area. Under farmers practice, current yield is about 7.5 t/ha for Shanyou63 and 6.5 t/ha for Xieyou46. There is a gap between the actual rice yield and the potential yield for these two hybrid rice varieties grown in this area. The attainable target yields were set to 70% to 75% of their potential yields for the two varieties. A recently developed software "Nutrient Decision Support System (NuDSS)" for irrigated rice was used to optimize nutrient management for these two rice varieties. According to NuDSS, the optimal fertilizer N requirement for the target yields was about 150 kg/ha for Shanyou63 and about 120 kg/ha for Xieyou46, which were only about 70% of the fertilizer N application under current farmers' practice. Comparing with farmers' practice, there is great potential to increase actual rice yields and to reduce fertilizer N use rates by improving rice crop management practice in Jinhua.

Key words: Rice, WOFOST, NuDSS, Potential growth, Nitrogen management
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INTRODUCTION

Rice production is important in Zhejiang Province. About 70% of food crop sowing area and 83% of total food yield in Zhejiang is rice, and rice is staple for 95% of Zhejiang dwellers who live on rice (Fang *et al*., 2004). Among the 1.028 million ha sown rice in Zhejiang in 2005, about 86% was mid-rice and late rice (Zhejiang Statistic Bureau, 2006). Mid-rice- and late rice-upland crops are the main rice-based cropping systems in Zhejiang. In central and southern Zhejiang, two of the widely-grown varieties are hybrid Shanyou63 for mid-rice and hybrid Xieyou46 for late rice. Under farmers' practice, the actual yield is about 7.5 t/ha for Shanyou63 and 6.5 t/ha for Xieyou46. However, there were high yield records of about 12 t/ha for Shanyou63 and 10 t/ha for Xieyou46 existed at the Agricultural Research Institute of Jinhua, which could be the highest yield records. On average, farmers' current fertilizer N application is about 220 kg/ha for Shanyou63 and 180 kg/ha for Xieyou46. According to recent reports (Wang *et al*., 2001a; 2001b; 2007; Peng *et al*., 2006; Jing *et al*., 2007; Xie *et al*., 2007), the current nutrient management practice in this area, especially that of N, seems to be very inefficient. The returns from higher rates of N application are low. There is potential to reduce the environmental damage resulted in overuse

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of N fertilizer and its loss to the atmosphere and the groundwater at Jinhua.

In rice production we need to set a target of attainable yield. The goal of attainable yield is based on the potential yield of specific variety defined as the maximum possible yield limited only by climatic conditions when there are no other factors limiting crop growth (Fairhurst and Witt, 2002). Potential yield is an important parameter for a rice variety in a specific locality, and it can be determined by using crop simulation models. WOFOST is a generic crop growth model that simulates crop production potential by climate and crop characteristics (van Diepen *et al*., 1989; Bouman *et al*., 1996). Currently WOFOST version 7.1 is widely used (Boogaard *et al*., 1998). Following the dynamic calculation of potential yields, the static procedure known as QuEFTS (Quantitative Evaluation of the Fertility of Tropical Soil) procedure is used to calculate nutrient-limited yield (Janssen *et al*., 1990). In northern China, QuEFTS is used to simulate winter wheat production (Wu *et al*., 2003).

The recently developed software "Nutrient Decision Support System (NuDSS)" for irrigated rice is based on QuEFTS procedure and the recent research results on site-specific nutrient management (SSNM) for rice in the irrigated lowlands (Witt *et al*., 2005; Pampolino *et al*., 2007). It is used to estimate the nutrient requirements based on attainable yields and indigenous nutrient supply in irrigated rice, decision is then made on whether to split application of the fertilizer, the profit gained was then estimated using the improved nutrient and crop management programs. It is successfully used in the SSNM network of Asia (IRRI-IRRC, 2006).

The objectives of this study were to: (1) simulate the yield potential of Shanyou63 and Xieyou46 in Jinhua of Zhejiang by WOFOST model; (2) optimize fertilizer N, P, K application by utilizing NuDSS software for the two hybrid rice varieties.

MATERIALS AND METHODS

Experimental design

Rice field experiments were conducted from 1999 to 2002 for Xieyou46 and from 2001 to 2002 for Shanyou63 at Shimen State Farm (29°7′ N, 119°39′ E, 64 m altitude), Jinhua of Zhejiang Province. Some basic properties of the soils before the experiments are given in Table 1. Xieyou46 was grown as late rice, sown in the middle of June, transplanted on around 20 July, reached maturity around Oct. 20. Shanyou63 was grown as mid-rice, sown in late May, transplanted in late June, reached maturity in early October. Phosphorus at 25 kg P/ha for Xieyou46 and 40 kg P/ha for Shanyou63, potassium at 100 kg K/ha and zinc at 5 kg Zn/ha for both varieties, all the P, K, Zn were applied as basal fertilizers for all treatments. The fertilizer N treatments for Xieyou46 were 150 kg N/ha (from 1999 to 2000), and 180 kg N/ha (from 2000 to 2001), with 50% applied as basal fertilizer, and 25% at early tillering, and another 25% at panicle initiation. The fertilizer N treatments for Shanyou63 included control (no-N), 120, and 180 kg N/ha, with 35% applied as basal fertilizer, 20% at early tillering, 30% at panicle initiation and 15% at heading. Zero N application was used as check. The plot size was 45 m^2 with 3 replicates for Xieyou46, and 30 m^2 with 4 replicates for Shanyou63, both arranged in randomized complete block design. The spacing between hills was 20 cm×20 cm with one seeding per hill. The plots were kept flooded throughout the growing season. Pests, diseases, weeds were intensively controlled to avoid yield loss.

Table 1 Some basic properties of the soils

	Xieyou46	Shanyou63
pH	4.80	4.50
Org. C (g/kg)	16.5	16.1
Total N (g/kg)	2.70	1.68
Olsen-P (mg/kg)	16.5	28.5
Exch. K (cmol/kg)	0.14	0.13
CEC (cmol/kg)	8.02	5.40
Sand (g/kg)	278	280
Silt (g/kg)	562	585
Clay (g/kg)	160	135

Plant sampling and measurements

One hundred seedlings at transplanting, and a 12-hill plant sample of each plot at mid-tillering, panicle initiation, flowering, and physiological maturity stages were collected. Plant samples were separated into leaves, stems plus sheaths, panicles, and grains. Yield composition was also determined at physiological maturity. Each sample was oven-dried at 70 °C till constant weight. Tissue N concentration was determined by micro Kjeldahl method (Lu, 1999). Grain yield was determined from 125 hills of the plants at maturity. Leaf area was calculated from the leaf dry weight with a conversion coefficient at different growth stages (Zheng and Lou, 1997; Bouman *et al*., 2001).

Weather data

The weather data for WOFOST simulation include daily maximum temperature (°C), minimum temperature (°C), irradiation [kJ/(m^2·d)], early morning vapor pressure (kPa), and mean wind speed at 2 m above ground (m/s). Weather information was obtained from Jinhua weather station.

RESULTS

Yield potential simulation by WOFOST model

1. Calibrated and revised parameters of WOFOST

In this study, WOFOST model was used to simulate the potential production. WOFOST simulates annual crop growth at time steps of one day. The simulation is based on ecophysiological development, CO_2-assimilation, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation (Boogaard *et al*., 1998). There is a set of default parameters of IR72 for rice in WOFOST version 7.1. IR72 is a high yield rice variety bred by International Rice Research Institute and widely grown in the tropics (Bouman *et al*., 2001).

WOFOST divides rice growth to three key development stages: emergence (0), flowering (1), and physiological maturity (2). We calibrated the length of growth period and phenology for Xieyou46 and Shanyou63 using the field experiment results given in Table 2.

Table 2 Calibrated parameters in WOFOST for Shanyou63 and Xieyou46

	Shanyou63	Xieyou46
*TSUM*1 (°C·d)	1690	1640
*TSUM*2 (°C·d)	550	450
DVSI	0.23	0.38
TDWI (kg/ha)	100	100
LAIEM (ha/ha)	0.01	0.01
RGRLAI [ha/(ha·d)]	0.009	0.007

*TSUM*1 is temperature sum from emergence to flowering; *TSUM*2 is temperature sum from flowering to maturity; *DVSI* is development stage at simulation initialization; *TDWI* is total plant dry weight at transplanting; *LAIEM* is leaf area index at transplanting; *RGRLAI* is maximum relative increase in leaf area index

According to the model, part of carbohydrates produced by plant is used to provide energy for the maintenance of the existing live biomass. The remaining carbohydrates are converted into structural matter. In this conversion, some of the weight is lost as growth respiration. The dry matter produced is partitioned among the various plant organs such as roots, leaves, stems and storage organs, using partitioning factors that are a function of the phenological development stage of the crop. Based on the results of these field experiments and other experiments conducted at the same area (Zheng and Lou, 1997; Yan *et al*., 1998; Wang *et al*., 2004), some of the crop growth parameters of the default values (IR72) in WOFOST revised for Shanyou63 and Xieyou46 are shown in the function tables (Table 3). The data included in the tables are a fraction of dry matters partitioned to the roots, to the leaves, and to the stems as function of developmental stages. Specific leaf area, maximum rate of leaf CO_2 assimilation rate, and light extinction coefficient for leaves as function of developmental stages were also revised. Other default parameter values of IR72 in WOFOST were adapted.

2. Potential yields of Xieyou46 and Shanyou63

The potential yield simulated with WOFOST is about 10 t/ha for Xieyou46, and 12 t/ha for Shanyou63, which are in good agreement with the highest yield records researchers had obtained in Jinhua. Under farmers' practice, actual yield is about 6.5 and 7.5 t/ha for Xieyou46 and Shanyou63, respectively, which accounts for 60%~65% of their potential yields. There is a gap between the actual yield and the potential yield for these two hybrid rice varieties grown in this area. This also means that the actual production situation in Jinhua has not reached the optimum condition. This could be due to the existing cultural practices currently used by farmers for crop management leading to imbalanced nutrient supply, insufficient supply of nitrogen to the plant growth stages in the mid-rice and late rice crops that are not favorable to crop production (Lu and Zou, 2000; Wang *et al*., 2004).

Table 3 Some revised parameters in WOFOST for Shanyou63 and Xieyou46

Function	Value
SLATB	A: 0.00, 0.0035; 0.40, 0.0030; 0.65, 0.0025; 1.00, 0.0020; 1.55, 0.0018; 2.00, 0.0018
	B: 0.00, 0.0037; 0.43, 0.0037; 0.74, 0.0030; 0.84, 0.0030; 1.00, 0.0029; 2.00, 0.0021
FRTB	A: 0.00, 0.50; 0.25, 0.35; 0.40, 0.32; 0.70, 0.20; 0.72, 0.00; 1.00, 0.00; 2.00, 0.00
	B: 0.00, 0.50; 0.43, 0.35; 0.65, 0.50; 0.80, 0.25; 0.85, 0.05; 1.00, 0.00; 2.00, 0.00
FLTB	A: 0.00, 0.65; 0.31, 0.65; 0.53, 0.54; 0.80, 0.40; 0.90, 0.20; 1.00, 0.00; 2.00, 0.00
	B: 0.00, 0.65; 0.50, 0.62; 0.60, 0.57; 0.80, 0.40; 0.85, 0.13; 1.00, 0.00; 2.00, 0.00
FSTB	A: 0.00, 0.35; 0.31, 0.35; 0.53, 0.46; 0.80, 0.60; 0.90, 0.30; 1.00, 0.00; 2.00, 0.00
	B: 0.00, 0.35; 0.50, 0.38; 0.60, 0.43; 0.80, 0.60; 0.85, 0.35; 1.00, 0.00; 2.00, 0.00
AMAXTB	A: 0.00, 40; 0.20, 45; 0.35, 40; 0.70, 40; 0.80, 50; 2.00, 50
	B: 0.00, 40; 0.75, 50; 0.85, 50; 1.00, 35; 1.90, 35; 2.00, 35
KDIFTB	A: 0.00, 0.40; 0.65, 0.40; 1.00, 0.50; 2.00, 0.60
	B: 0.00, 0.40; 0.65, 0.40; 1.00, 0.60; 2.00, 0.60

A, B stand for Shanyou63, Xieyou46, respectively; *SLATB*: Specific leaf area index (ha/ha) as a function of development stages (DVS); *FRTB*: Fraction of dry matter to roots as a function of DVS; *FLTB*: Fraction of dry matter to leaves as a function of DVS; *FSTB*: Fraction of dry matter to stems as a function of DVS; *AMAXTB*: Maximum leaf CO_2 assimilation rate [kg CO_2/(ha·h)] as a function of DVS; *KDIFTB*: Light extinction coefficient for leaves as a function of DVS

Optimize fertilizer N, P, K application with the NuDSS model

1. Attainable target yields

Rice yields are location- and season-specific depending upon climate, rice cultivars, and crop management. The yield target for a given location and season is the estimated grain yield attainable with farmers' crop management when the constraints of N, P and K are overcome (Fairhurst and Witt, 2002; Dobermann *et al*., 2004). Under farmers' practice, on average, the actual yield is about 6.5 and 7.5 t/ha for Xieyou46 and Shanyou63, respectively. However, in the high yield domains with better crop management usually a yield of 7.5 t/ha for Xieyou46 and 8.5 t/ha for Shanyou63 can be attained. Based on the yield potential simulated with WOFOST model, and current level of yield achieved in farmers' fields, we set a target of attainable yield of 8.5 t/ha for Shanyou63, about 10% higher than the actual yield, or about 70% of its yield potential, and 7.5 t/ha for Xieyou46, about 75% of its yield potential. We believe that these are the actual yields farmers can attain for these two varieties in Jinhua.

2. Estimating soil indigenous nutrient supplies

Soil indigenous N, P, K supply was used as input in NuDSS designed to estimate fertilizer requirements. Soil indigenous nutrient supply was defined as plant nutrient uptake with above-ground biomass in a nutrient omission plot in which only the nutrient of interest is limiting. Thus, total N uptake in a PK plot is used as an estimate of the indigenous N supply, total P uptake in a NK plot estimates the indigenous P supply, and total K uptake in an NP plot estimates the indigenous K supply. Therefore, the indigenous supply includes nutrients released from soil solids as well as inputs of plant available nutrients from non-fertilizer sources such as irrigation, rainfall, or biological N fixation during one crop season of rice.

Using grain yield in nutrient omission plots in a cropping season as an indicator of the soil indigenous supply of N, P, K, is more practical than measuring the plant nutrient uptake (Dobermann *et al*., 2003). The N-limited yield was measured from rice crop grown in N omission plot. The plot receives sufficiently large amount of fertilizer P and K. Similarly, the P-limited yield was measured from rice crop grown in P omission plot. The K-limited yield was measured from rice crop grown in K omission plot. The N-limited, P-limited, and K-limited yield in Jinhua are given in Table 4. The range of N-limited yield is usually 5.0 to 6.0 t/ha for Shanyou63 and 4.5 to 5.5 t/ha for Xieyou46 (Wang et *al*., 2001c; 2004; Peng *et al*., 2006).

3. Estimating fertilizer N, P, K requirement of rice

The core of the NuDSS is a generic approach to estimate crop nutrient uptake requirements (Witt *et al*., 1999). It accounts for interactions among macronutrients affecting the internal efficiencies (i.e., kg grain produced per kg plant nutrient) of N, P and K and allows differentiation according to different yield levels targeted. The NuDSS software assists in the development of improved fertilizer strategies that aim at effective fertilizer use, high and sustainable yields, and increased farmers' profit (Witt *et al*., 1999; 2005).

Knowledge of indigenous nutrient supply would allow calculation of fertilizer rates based on the general equations (Dobermann and Cassman, 2002):

$$Y=f(Y_m, U_1, \ldots U_x), \quad (1)$$
$$F_x=(U_x-IS_x)/R_x, \quad (2)$$

where Y is targeted yield, Y_m is yield potential for a certain location and cropping season, U_x is amount of nutrient that needs to be accumulated in the plant to achieve Y, F_x is amount of fertilizer that needs to be applied to achieve Y, IS_x is supply of nutrient from all indigenous (non-fertilizer) sources, R_x is fraction of fertilizer nutrient recovered in the plant, and the subscript x denotes each of the essential plant nutrients.

The input parameters needed in NuDSS are given in Table 4. The output by running the model is given in Table 5. Based on NuDSS output, under general soil fertility in Jinhua, for the yield target of 8.5 t/ha for Shanyou63 and 7.5 t/ha for Xieyou46, fertilizer N requirement is about 150 kg and 120 kg, respectively. This fertilizer N rate is only about 70% of the current rates used by farmers for these two varieties. This means that there is about 30% of fertilizer N over use by farmers. This helps to explain why fertilizer nitrogen use efficiency is usually poor, and profitability is not optimized.

Table 4 Input parameters to NuDSS for fertilizer requirement calculation

Variety	Shanyou63	Xieyou46
Yield potential (t/ha)	12.0	10.0
N-limited yield (t/ha)	5.5	5.0
P-limited yield (t/ha)	7.5	6.5
K-limited yield (t/ha)	7.0	6.0
Yield goal (t/ha)	8.5	7.5
Fertilizer recover efficiency		
N	0.40	0.40
P	0.25	0.25
K	0.45	0.45

Table 5 Fertilizer requirement calculated by NuDSS model

Variety	Shanyou63	Xieyou46
Yield goal (t/ha)	8.5	7.5
Fertilizer requirement (kg/ha)		
N	150	120
P	20	15
K	100	65

Across the whole area of Jinhua, grain yield in the farmers' fertilizer practice plot was higher than the no-N plots, suggesting a universal yield response to fertilizer N (Wang *et al.*, 2004). It confirms that N deficiency is a general feature of irrigated rice systems in this area. Fertilizer N has to be supplied every season as farmers do to maintain the attainable yield. Increasing in N-use efficiency is the key issue of N management. In contrast to N use, at the present yield level, the P and K supplies are not limiting factors in rice production. Rice farmers in Zhejiang usually apply 18 kg P/ha and 60~75 kg K/ha per season as basal fertilizer. Results of long-term fertilization experiments indicated that soil P and K supply decreased within a short time (3~4 seasons for P and 1~2 seasons for K), so that yields would decline, unless fertilizer P or K was applied in sufficient quantities (Wang *et al.*, 2001a). The major objective of P and K management is to prevent P and K deficiency rather than treat P- and K-deficiency symptoms. If low soil P or K is the reason that targeted yields are not achieved, management must be focused on building up and on maintenance of adequate soil-available P and K levels to ensure that P and K supply does not limit crop growth and N-use efficiency (Fairhurst and Witt, 2002). Sustainable P and K management requires the replenishment of soil P and K reserves, especially at high yield levels in intensive rice-cropping systems, even if a direct yield response to P and K application is not expected.

CONCLUSION

Mid-rice and late rice-upland crops are the main rice-based cropping systems in Zhejiang. Hybrid Shanyou63 for mid-rice and Xieyou46 for late rice crops are the main rice varieties grown in Jinhua. Under the subtropical climate condition of Jinhua, the yield potential is about 12 t/ha for Shanyou63 and 10 t/ha for Xieyou46 simulated using WOFOST model. Based on the yield potential, the general indigenous nutrient supply of the soil, and the crop management practice in Jinhua, attainable yields of 8.5 t/ha for Shanyou63 and 7.5 t/ha for Xieyou46 were feasible. Knowledge-intensive software of NuDSS was utilized to calculate nutrient N, P, K requirements to obtain the target yields for these two rice varieties. According to

NuDSS, the optimal fertilizer N requirement for the target yields is about 150 kg/ha for Shanyou63 and 120 kg/ha for Xieyou46, which are only about 70% of the current fertilizer N use in farmers' fields. Comparing with farmers' practice, there is a great potential for the rice farmers to increase actual yields and to reduce the rate of fertilizer N use by improving their crop management practice in this area.

References

Boogaard, H.L., van Diepen, C.A., Rotter, R.P., 1998. User's Guide for the WOFOST7.1: Crop Growth Simulation Model and WOFOST Control Center. Winand Staring Centre, DLO Wageningen, p.1-40.

Bouman, B.A.M., van Keulen, H., van Laar, H.H., Rabbinge, R., 1996. The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. *Agric. Syst.*, **52**(2-3):171-198. [doi:10.1016/0308-521X(96)00011-X]

Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., ten Berge, H.F.M., van Laar, H.H., 2001. ORYZA2000: Modeling Lowland Rice. International Rice Research Institute, and Wageningen University and Research Centre, p.235.

Dobermann, A., Cassman, K.G., 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. *Plant Soil*, **247**(1):153-175. [doi:10.1023/A:1021197525875]

Dobermann, A.C., Witt, C., Dawe, D., Gines, G.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., *et al*., 2003. Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia. *Agron. J.*, **95**(4):913-923.

Dobermann, A., Witt, C., Dawe, D., 2004. Increasing the Productivity of Intensive Rice Systems through Site-Specific Nutrient Management. Science Publishers Inc., and International Rice Research Institute (IRRI), Enfield, NH (USA) and Los Baños (Philippines), p.1-420.

Fairhurst, T.H., Witt, C., 2002. Rice: A Practical Guide for Nutrient Management. Potash and Phosphate Institute & Potash and Phosphate Institute of Canada and International Rice Research Institute, Singapore and Los Baños.

Fang, F.P., Zhang, X.F., Wang, D.X., 2004. Rice potential yield of Zhejiang Province and a discussion about science and technology countermeasure. *J. Zhejiang Agric. Sci.*, **5**:237-239 (in Chinese).

IRRI-IRRC (International Rice Research Institute-Irrigated Rice Research Consortium), 2006. http://www.irri.org/irrc

Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J., van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QuEFTS). *Geoderma*, **46**(4):299-318. [doi:10.1016/0016-7061(90)90021-Z]

Jing, Q., Bouman, B.A.M., Hengsdijk, H., van Keulen, H., Cao, W., 2007. Exploring options to combine high yields with high nitrogen use efficiencies in irrigated rice in China. *Eur. J. Agronomy*, **26**(2):166-177. [doi:10.1016/j.eja.2006.09.005]

Lu, R.K., 1999. Soil Agrochemistry Analysis. China Agricultural Scientech Press, Beijing, p.147-149 (in Chinese).

Lu, C.G., Zou, J.S., 2000. Breeding and utilization of a two-line intersubspecific hybrid Liangyoupeijiu. *Hybrid Rice*, **15**(2):4-5 (in Chinese).

Pampolino, M.F., Manguiat, I.J., Ramanathan, S., Gines, H.C., Tan, P.S., Chi, T.T.N., Rajendran, R., Buresh, R.J., 2007. Environmental impact and economic benefits of site-specific nutrient management (SSNM) in irrigated rice systems. *Agric. Syst.*, **93**(1-3):1-24. [doi:10.1016/j.agsy.2006.04.002]

Peng, S., Buresh, R.J., Huang, J., Yang, J., Zhou, Y., Zhong, X., Wang, G., Zhang, F., 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crops Research*, **96**(1):37-47. [doi:10.1016/j.fcr.2005.05.004]

van Diepen, C.A., Wolf, J., van Keulen, H., Rappold, C., 1989. WOFOST: a simulation model of crop production. *Soil Use Manage.*, **5**(1):16-24. [doi:10.1111/j.1475-2743.1989.tb00755.x]

Wang, G.H., Dobermann, A., Witt, C., Sun, Q.Z., Fu, R.X., 2001a. Performance of site-specific nutrient management for irrigated rice in Southeast China. *Agron. J.*, **93**:869-878.

Wang, G.H., Dobermann, A., Witt, C., Sun, Q.Z., Fu, R.X., 2001b. A new approach to increase the attainable rice yield in intensive irrigated rice systems of Zhejiang Province, China. *J. Zhejiang Univ. Sci.*, **2**(2):196-203.

Wang, G.H., Dobermann, A., Witt, C., Fu, R., Sun, Q., 2001c. Analysis on the indigenous nutrient supply capacity of rice soils in Jinhua, Zhejiang Province. *Chin. J. Rice Sci.*, **15**(3):201-205 (in Chinese).

Wang, G., Sun, Q., Fu, R., Huang, X.H., Wu, J., He, Y.F., Dobermann, A., Witt, C., 2004. Site-Specific Nutrient Management in Intensive Irrigated Rice Systems of Zhejiang Province, China. *In*: Dobermann, A., Witt, C., Dawe, D. (Eds.), Increasing Productivity of Intensive Rice Systems through Site-Specific Nutrient Management. Science Publishers Inc., Enfield NH, USA, and International Rice Research Institute (IRRI), Los Baños, Philippines, p.243-264.

Wang, G.H., Zhang, Q.C., Witt, C., Buresh, R.J., 2007. Opportunities for yield increases and environmental benefits through site-specific nutrient management in rice systems of Zhejiang Province, China. *Agric. Syst.*, **94**(3):801-806. [doi:10.1016/j.agsy.2006.11.006]

Witt, C., Dobermann, A., Abdulrachman, S., Gines, H.C., Wang, G.H., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Tiem, L.V., *et al*., 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. *Field Crops Res.*, **63**(2):113-138. [doi:10.1016/S0378-4290(99)00031-3]

Witt, C., Fairhurst, T.H., Sheehy, J.E., Dobermann, A., Gfroerer Kerstan, A., 2005. A Nutrient Decision Support

System (NuDSS) for Irrigated Rice. PPI/PPIC and IPI, Singapore, and IRRI, Los Banos, Philippines.

Wu, D.R., Qu, Y.Z., Zhao, X.M., 2003. The application research of WOFOST model in North China Plain. *Acta Phytoecologica Sinica*, **27**(5):594-602 (in Chinese).

Xie, W.X., Wang, G.H., Zhang, Q.C., Guo, H.C., 2007. Effects of nitrogen fertilization strategies on nitrogen use efficiency in physiology, recovery, and agronomy and redistribution of dry matter accumulation and nitrogen accumulation in two typical rice cultivars in Zhejiang, China. *J. Zhejiang Univ. Sci. B*, **8**(3):208-216. [doi:10.1631/jzus.2007.B0208]

Yan, L.J., Wang, Z.Q., Du, J.S., Pan, D.Y., Lu, Q.H., Yin, Z.X., 1998. Establishment and validation of simulation model for rice production. *J. Biomath.*, **13**(2):223-229 (in Chinese).

Zhejiang Statistic Bureau, 2006. Statistic Yearbook of Zhejiang. Chinese Statistic Press, Beijing (in Chinese).

Zheng, Z.M., Lou, Y.C., 1997. Simulation of potential production and studies on optimum population quantitative indexes on hybrid rice. *J. Zhejiang Agric. Univ.*, **23**(1):59-64 (in Chinese).