

EVALUATION OF THE ORYZA2000 RICE GROWTH MODEL UNDER NITROGEN-LIMITED CONDITIONS IN AN IRRIGATED MEDITERRANEAN ENVIRONMENT

Pamela Artacho^{1*}, Francisco Meza¹, and José Antonio Alcalde¹

ABSTRACT

ORYZA2000 is a growth model for tropical lowland rice (*Oryza sativa* L.) developed by the International Rice Research Institute and Wageningen University. This model has been evaluated extensively in a wide range of environments. However, reports examining japonica cultivars growing in temperate climates are scarce. In this study, ORYZA2000 was calibrated and evaluated using data from experiments carried out in the South-Central area of Chile. These experiments were performed on a japonica rice cultivar growing under an irrigated Mediterranean environment at various N rates. ORYZA2000 was then applied to explore potential yield and grain yield response to N fertilization under likely weather conditions in the major rice-producing area in Chile. ORYZA2000 was sufficiently accurate to simulate grain yield and crop N uptake at the end of the season. Final crop N uptake was simulated with a root mean squared error (RMSE) of 20 kg ha⁻¹ (15%) and grain yield with a RMSE of 1666 kg ha⁻¹ (19%). However, the prediction of biomass and N uptake of individual organs throughout the season was poor. A long-term simulation study confirmed a potential yield as high as 12 000 kg ha⁻¹ in the Parral area, as well as the existence of a scope for yield increase. The yield response to N fertilization was predicted even at rates of 300 kg ha⁻¹, although a significant probability of low yields was also observed. This trend supports the need to incorporate dynamic N management in Chilean rice production.

Key words: ORYZA2000 model, irrigated rice, nitrogen, Mediterranean environment, Chile.

INTRODUCTION

Rice (*Oryza sativa* L.) is grown in a wide range of locations and climatic conditions and under a variety of hydrologic, cultural and seasonal regimes around the world. In Chile, rice is grown between 34°10' and 36°36' S latitudes in an irrigated Mediterranean environment, using a few japonica cultivars. Under these conditions, N is the most important nutrient and high yields are associated with large N applications. However, N recovery efficiency is low in flooded culture because of N losses, primarily due to ammonia volatilization. Measurements in field trials show efficiencies lower than 50%, in both tropic (Fageria and Baligar, 2001) and temperate climates (Carreres *et al.*, 2000). However, efficiencies close to 70% can be achieved by fertilizer application at the proper rate and time (Peng and Cassman, 1998).

N-fertilizer recommendations are usually based on field trials with various N-fertilizer rates to determine optimum rates, which are then used as recommendations for larger areas. Other recommendation systems use "expected" yields and N content to estimate the crop N demand (Rodríguez *et al.*, 2001). However, yield is highly variable as a result of differences in soil and climate conditions, being difficult to predict. In this sense, crop simulation models in combination with field experiments are useful tools to improve N-fertilizer recommendations by matching soil N supply with crop N demand (Haeefe *et al.*, 2003; Segda *et al.*, 2005). Simulation models synthesize current insights in crop growth processes, and predict crop performance under different soil, climate and management conditions. Various models exist for rice, such as ORYZA2000 (Bouman *et al.*, 2001), CropSyst (Stöckle *et al.*, 2003), CERES-Rice (Jones *et al.*, 2003), Infocrop (Aggarwal *et al.*, 2006), and APSIM-ORYZA (Zhang *et al.*, 2007). These models have been used to study a wide range of issues, such as mixed cropping, production potential, alternative management practices, yield forecasting, and to assess the impacts of climatic variability and change.

¹Pontificia Universidad Católica de Chile, Facultad de Agronomía e Ingeniería Forestal, Av. Vicuña Mackenna 4860, Santiago, Chile.
 *Corresponding author (pnartach@uc.cl).

Received: 22 May 2010.

Accepted: 25 October 2010.

In the mid-1990s, the International Rice Research Institute (IRRI) and Wageningen University developed the ORYZA model series to simulate the dynamics of growth and development of tropical lowland rice for potential, water- and N-limited conditions. ORYZA2000 is an updated integration of these models, and has been evaluated under N-limited conditions in the Philippines (Bouman and van Laar, 2006) and China (Jing *et al.*, 2007; Tang *et al.*, 2009), and under water-limited conditions in Indonesia (Boling *et al.*, 2007), China (Xue *et al.*, 2005; Feng *et al.*, 2007), the Philippines (Belder *et al.*, 2007) and India (Arora, 2006; Soundharajan and Sudheer, 2009). These authors reported satisfactory results in most cases. Calibration and evaluation reports for japonica cultivars growing under N-limited conditions are scarce, especially in temperate climates. Therefore, the objectives of this study were to (a) calibrate and evaluate ORYZA2000 performance for a japonica cultivar growing in an irrigated Mediterranean environment with different levels of N fertilizer, and (b) apply ORYZA2000 to explore potential yields and grain yield response to N fertilization under likely weather conditions in the major rice-producing area in Chile.

MATERIALS AND METHODS

ORYZA2000 was calibrated using a data set from a field experiment conducted during the 2006-2007 growing season. The model was then evaluated for biomass and N-related variables at the end of the season using an independent data set from field experiments conducted during the 2005-2006 season (Table 1). For dynamic biomass and N-related variables, a preliminary evaluation was performed using the calibration data set. Finally, ORYZA2000 was used to explore potential yields and grain yield variability due to N fertilization, using 100-years of synthetic weather data generated from weather records of the major rice-producing area in Chile.

The ORYZA2000 model

ORYZA2000 is a crop model that simulates growth and development of lowland rice for potential, water- and N-limited production situations. In all situations, it is assumed that the crop does not suffer yield reductions due other stresses. A brief description of the modules for potential and N-limited production situations follows. For a detailed explanation, see Bouman *et al.* (2001).

The model simulates daily dry matter (DM) increases in plant organs and phenological development progress. By integrating these rates over time, DM production and development stage are simulated throughout the growing season. The development stage is tracked as a function of daily mean temperature and photoperiod. On

Table 1. Data sets used in calibration and validation procedures of the ORYZA2000 model.

Experiment set	Location	Latitude; longitude	Growing season	N rates (kg N ha ⁻¹)	Fertilizer N split
Calibration set					
TUC 06-07	Experimental Station Tucapel	36.10° S; 71.88° W	2006-2007	0, 75, 150, 225, and 300	100% ps
Validation set					
TUC 05-06	Experimental Station Tucapel	36.10° S; 71.88° W	2005-2006	0, 50, 100, 150, 200, and 300	100% ps
SIS 05-06	Santa Isabel plot	36.30° S; 72.02° W	2005-2006	0, 50, 100, 150, 200, and 300	100% ps
UN 05-06	Unicaven plot	36.07° S; 72.00° W	2005-2006	0, 100, and 200	100% ps
TUC _p 05-06	Experimental Station Tucapel	36.10° S; 71.88° W	2005-2006	100	100% ps
				100	75% ps; 25% ti
				100	50% ps; 50% ti
				100	75% ps; 25% pi
				100	50% ps; 50% pi
				100	40% ps; 30% ti; 30% pi

ps: pre-sowing; ti: tillering initiation; pi: panicle initiation.

the basis of single leaf photosynthetic characteristics, instantaneous rates of CO₂ assimilation are calculated at three moments during the day and at three depths in the canopy. Integration over total leaf area and over the day, yields gross daily assimilation rates. Net daily growth rate is obtained by subtracting maintenance and growth respiration requirements, and then is partitioned into roots, leaves, stems and panicles, using experimentally derived factors. Leaf area grows exponentially as a function of temperature sum when the canopy is not yet closed. Then, leaf area grows linearly and is calculated from the increase in leaf weight times a specific leaf area. Spikelet number at flowering is obtained from the biomass accumulated between panicle initiation and flowering, taking into consideration spikelet sterility due to either too high or too low temperatures. Daily potential N demand is calculated from the dry weight, growth rate, and N concentration of each plant organ. The basic model assumption is that crop strives to maintain maximum N concentrations in leaves and stems. N demand of the vegetative organs is satisfied through crop N uptake, which is limited by the maximum uptake rate of the plant and by the maximum available amount of N in the soil. Panicle demand is satisfied through N translocation from vegetative organs. Soil N availability is modeled from indigenous soil N and fertilizer N, without simulating any N transformation processes in the soil. The effect of N limitations on leaf area growth is accounted for a reduction factor based on the actual and maximum leaf N concentration, and the effect of N stress on leaf loss by a factor based on the actual and potential amount of N in the crop (Bouman *et al.*, 2001; van Ittersum *et al.*, 2003; Bouman and van Laar, 2006; Jing *et al.*, 2007).

Calibration of the ORYZA2000 model

ORYZA2000 was calibrated according to Bouman *et al.* (2001). The crop parameters calibrated were: development rates (DVR); assimilate partitioning factors to leaves, stems and storage organs (FLV, FST and FSO, respectively); specific leaf area (SLA); leaf death rate (DRLV); and fraction of stem reserves (FSTR) (Table 2). The N-related parameters calibrated were: N fraction in leaves on area basis (NFLV); residual N concentration in leaves (RFNLV) and stems (RFNST); initial leaf N concentration (FNLVI); initial N fraction in leaves on area basis (NFLVI); maximum and minimum N concentration in storage organs (NMAXSO and NMINSO, respectively); maximum and minimum leaf N concentration (NMAXL and NMINL, respectively); maximum daily N uptake (NMAXUP); and recovery fraction of fertilizer N (RECNIT) (Table 2). The parameters derived from the literature were: cardinal temperatures, relative leaf growth rate (RGRL) and maximum grain weight (WGRMX)

(Table 2). In addition, a neutral photoperiod response was considered for the cv. Diamante-INIA. For assimilate partitioning factors and SLA, the calibrated parameters were further fine-tuned by matching simulated and measured values of related variables. All other parameters were set to values from the standard crop data file of ORYZA2000 for the tropical variety IR72.

Evaluation of ORYZA2000 model

ORYZA2000 was run under conditions observed in field experiments. All calibrated parameters were used to simulate each experiment, except for development rates that were treatment-specific (DVR; Table 2). Then, graphical analysis and statistical measures were carried out, following Bouman and van Laar (2006) and Jing *et al.* (2007). Simulated and measured total biomass, biomass of individual organs, crop N uptake, and N uptake of individual organs, were compared graphically. For the same variables, ORYZA2000 performance was evaluated by looking at the absolute and normalized root mean squared error (RMSE) between simulated and measured values, calculated as:

$$RMSE_a = (1/n \sum (Y_i - X_i)^2)^{0.5} \quad RMSE_n = 100 \times \frac{(1/n \sum (Y_i - X_i)^2)^{0.5}}{\sum Y_i / X_i}$$

where n is the number of observations, and Y is the mean value of measured parameters from three replicates of the field trials. Additionally, a Student's *t*-test of means (*P*(*t*)) assuming unequal variance was applied for end-of-season variables.

Field experiments

Data were collected in five experiments carried out between 2005 and 2007 at the major rice-producing area in Chile (Parral Commune, Maule Region; Table 1). Soils had a clayey texture, flat topography, slow permeability and imperfect drainage. These were classified as Abruptic Durixeralf (UN 05-06 experiment) or Aquic Durixerert (other experiments), according to Soil Taxonomy-USDA (CIREN, 1994; 1997). In all cases, soils were acid, with low organic matter content (< 3%), and with medium to low levels of available K and B. 'Diamante-INIA', a japonica cultivar widely grown by Chilean farmers, was used in all trials. This is a mid-season cultivar with a high tillering ability and lodging resistance (Alvarado and Pino, 1982). Fields were flooded 3 d before sowing and water level was maintained between 10 and 15 cm depth until maturity. Sowing was performed within the optimum period for this agroclimatic area (mid-October to early November), at a rate of 150 kg seed ha⁻¹ by hand broadcasting.

Table 2. Summary of the calibrated values of main ORYZA2000 parameters for rice cultivar Diamante-INIA.

Model parameter	Calibrated value	Data source
Crop parameters		
Cardinal temperatures	10 °C (base); 28 °C (optimum); 40 °C (maximum)	Casanova <i>et al.</i> , 2000
DVRI, 10 ⁻³ (°C d ⁻¹)	2.126 ± 0.000; (mean ± standard error)	Calibration experiment
DVRI, 10 ⁻³ (°C d ⁻¹)	0.758 ± 0.000; (mean ± standard error)	Calibration experiment
DVRR, 10 ⁻³ (°C d ⁻¹)	0.984 ± 0.030; (mean ± standard error)	Calibration experiment
DVRR, 10 ⁻³ (°C d ⁻¹)	2.202 ± 0.041; (mean ± standard error)	Calibration experiment
RGRL, °C d ⁻¹	0.0028 (maximum); 0.0018 (minimum)	Casanova <i>et al.</i> , 2000
SLA, ha leaf kg ⁻¹ leaf	[DVS, SLA]: 0.00, 0.0030; 0.50, 0.0030; 0.65, 0.0028; 1.00, 0.0020; 1.37, 0.0017; 2.05, 0.0003.	Calibration experiment
SSGA, ha stem kg ⁻¹ stem	[DVS, SLA]: 0.00, 0.00; 0.65, 0.00; 1.00, 0.00; 2.05, 0.00.	Casanova <i>et al.</i> , 2000
FSTR	0.10	Calibration experiment
WGRMX, kg grain ⁻¹	0.00003043	Alvarado y Hernaiz, 2005
FSH	[DVS, FSH]: 0.0, 0.5; 0.4, 0.7; 0.7, 0.9; 1.0, 0.9; 2.5, 0.9.	Standard crop data file
FLV	[DVS, FLV]: 0.0, 0.50; 0.4, 0.50; 0.7, 0.35; 1.0, 0.10; 1.3, 0.00; 2.5, 0.00.	Calibration experiment
FST	[DVS, FST]: 0.0, 0.50; 0.4, 0.50; 0.7, 0.55; 1.0, 0.20; 1.3, 0.00; 2.5, 0.00.	Calibration experiment
FSO	[DVS, FSO]: 0.0, 0.00; 0.4, 0.00; 0.7, 0.10; 1.0, 0.70; 1.3, 1.00; 2.5, 1.00.	Calibration experiment
DRLV, d ⁻¹	[DVS, DRLV]: 0.00, 0.0000; 0.50, 0.0004; 0.65, 0.0005; 1.00, 0.0006; 1.30, 0.0006; 2.05, 0.0017.	Calibration experiment
N-related parameters		
NFLV, g N m ⁻² leaf	[DVS, NFLV]: 0.00, 1.43; 0.20, 1.43; 0.50, 1.32; 0.65, 1.27; 1.00, 1.15; 1.37, 1.03; 2.05, 0.82	Calibration experiment
NMAXUP, kg N ha ⁻¹ d ⁻¹	8	Calibration experiment
RFNLV, kg N kg ⁻¹ DM	0.004	Calibration experiment
RFNST, kg N kg ⁻¹ DM	0.0023	Calibration experiment
FNLVI, g N m ⁻² leaf	1.43	Calibration experiment
NMAXSO, kg N kg ⁻¹ DM	0.014	Calibration experiment
NMINSO, kg N kg ⁻¹ DM	[ANCRF (kg N ha ⁻¹), NMINSO]: 0, 0.008; 50, 0.008; 150, 0.011; 200, 0.012; 300, 0.013; 400, 0.014; 500, 0.014.	Calibration experiment
NMAXL, kg N kg ⁻¹ DM	[DVS, NMAXL]: 0.00, 0.042; 0.50, 0.042; 0.65, 0.036; 1.00, 0.022; 1.37, 0.019; 2.05, 0.015.	Calibration experiment
NMINL, kg N kg ⁻¹ DM	[DVS, NMINL]: 0.00, 0.017; 0.50, 0.017; 0.65, 0.016; 1.00, 0.012; 1.37, 0.007; 2.05, 0.005.	Calibration experiment
RECNT, kg N kg N ⁻¹	[DVS, RECNT]: 0.00, 0.30; 0.50, 0.35; 0.65, 0.58; 1.00, 0.80; 1.37, 0.60; 2.05, 0.50.	Calibration experiment

DVRI: development rate for the basic vegetative phase; DVRI: development rate for the photoperiod-sensitive phase; DVRR: development rate for the panicle formation phase; DVRR: development rate for the grain-filling phase; RGRL: relative leaf growth rate; SLA: specific leaf area; SSGA: specific green stem area; FSTR: fraction of stem reserves; WGRMX: maximum grain weight; FSH: fraction of total dry matter partitioned to the shoot; FLV, FST and FSO: assimilate partitioning factors to leaves, stems and storage organs, respectively; DRLV: leaf death rate; NFLV: N fraction in leaves on area basis; NMAXUP: maximum daily N uptake; RFNLV and RFNST: residual N concentration in leaves and stems, respectively; FNLVI: initial leaf N concentration; NMAXSO and NMINSO: maximum and minimum N concentration in storage organs, respectively; NMAXL and NMINL: maximum and minimum leaf N concentration, respectively; RECNT: recovery fraction of fertilizer N.

Daily weather data (maximum and minimum air temperature, precipitation, irradiance, mean wind speed and vapor pressure) were collected from automatic stations located at each site. In the calibration experiment (TUC 06-07), the experimental design was a three-replicate randomized complete block with five N fertilization levels (Table 1), which were applied as a single incorporated application of urea (46% N) prior to flooding. Experimental units were 24 m² plots surrounded by 30 cm height banks. Each plot was fertilized with 60 kg P₂O₅ ha⁻¹ (as triple superphosphate, 46% P₂O₅), 200 kg K₂O ha⁻¹ (as potassium chloride, 60% K₂O), and 2 kg B ha⁻¹ (as borax, 10% B). Harvest occurred between 13 April and 9 May 2007, depending on N rate. Phenological development was recorded at tillering, panicle initiation, flowering, milk grain, and maturity. At these stages, plants from a 0.25 m² sample area per experimental unit were randomly harvested and separated into green leaves, yellow/dead leaves, stems (culms plus sheaths) and panicles. Vegetal samples were oven-dried for 48 h at 70 °C to constant weight and N concentration was determined by Kjeldahl method. At maturity, panicles from a 1 m² sample area per experimental unit were harvested and hand-threshed. Grain weight adjusted to 14% moisture content was used as a yield estimate. In TUC 05-06 and SIS 05-06 experiments, six N rates were applied. In UN 05-06 experiment, three N rates were applied (Table 1). In the TUC_P 05-06 experiment, a single N rate was applied as urea in different splits (Table 1). Rice was harvested between 20 and 31 March 2006, depending on N rate. For each measured variable, standard error (SE), coefficient of variation (CV), mean, and standard deviation (SD) were calculated (Table 3).

Application of the ORYZA2000 model

One hundred consecutive years of daily weather data were generated based on weather statistics observed in the Parral area, which were used to fit a weather generator algorithm (Richardson, 1981; Meza *et al.*, 2003). Two simulation sets were carried out. In the first set, ORYZA2000 was run in the potential production mode to explore potential yield variability due to weather variation. In the second set, the model was run in the N balance mode using four fertilization rates (0, 100, 200, and 300 kg N ha⁻¹) as single applications at pre-sowing, in combination with two indigenous soil N supply levels (0.5 and 0.65 kg N ha⁻¹ d⁻¹). The effects of N fertilization on grain yield, as well as those of the weather conditions on potential yields were graphically analyzed as cumulative probability curves. Similar studies and graphical analyses have been carried out

Table 3. Evaluation results of ORYZA2000 simulations of crop variables throughout the entire growing season for the calibration data set (2006-2007 season), and of crop variables at the end of the season for the validation data sets (2005-2006 season).

Crop variable	n	SE	CV (%)	X _m (SD)	X _s (SD)	RMSE _a	RMSE _n (%)
Over entire growing season							
Total biomass, kg ha ⁻¹	25	1090	18	11478 (7432)	10829 (7951)	2161	19
Stem biomass, kg ha ⁻¹	25	639	19	6184 (4278)	4625 (3466)	2273	37
Green leaf biomass, kg ha ⁻¹	25	351	36	1924 (1203)	2028 (1110)	902	47
Dead leaf biomass, kg ha ⁻¹	25	167	29	1110 (1012)	892 (1015)	417	38
Panicle biomass, kg ha ⁻¹	25	459	21	2411 (2652)	3321 (2993)	1745	72
Crop N uptake, kg ha ⁻¹	25	16	24	114 (66)	92 (45)	41	36
Stem N uptake, kg ha ⁻¹	25	8	29	44 (31)	28 (16)	26	59
Green leaf N uptake, kg ha ⁻¹	25	7	42	39 (29)	36 (15)	18	44
Dead leaf N uptake, kg ha ⁻¹	25	1	28	8 (6)	5 (7)	5	57
Panicle N uptake, kg ha ⁻¹	25	7	27	26 (28)	25 (25)	10	38
At end of season							
Final crop biomass, kg ha ⁻¹	21	1245	14	16852 (3647)	19706 (3721)	4214	25
Grain yield, kg ha ⁻¹	21	827	17	8909 (2140)	8999 (1545)	1666	19
Final crop N uptake, kg ha ⁻¹	21	11	15	136 (42)	140 (31)	20	15

n: total number of data; SE: standard error of measured values; CV: coefficient of variation of measured values; X_m: mean of measured values; X_s: mean of simulated values; SD: standard deviation; RMSE_a: absolute root mean squared error between simulated and measured values; RMSE_n (%): normalized root mean squared error between simulated and measured values.

for modeling the effects of N management on wheat production in Australia (O'Leary and Connor, 1998) and the USA (Saseendran *et al.*, 2004).

RESULTS

Evaluation of ORYZA2000 model

Figure 1 compares simulated with measured crop variables throughout the season for the calibration data set, displays a 1:1 line \pm mean CV of measured data as reference. The dynamic of the total biomass was reproduced quite well for an ample range of N rates (0 to 300 kg N ha⁻¹). The majority of data points fell between the \pm CV lines, confirming the good fit between simulated and measured data. However, a wider spread of data was observed for biomass of individual organs. For panicle and green leaf biomass, data points falling outside of the \pm CV lines were found above the +CV line, indicating a general overestimation. In contrast, an underestimation by the model was observed for stem biomass (Figure 1). These discrepancies were reflected in higher normalized and absolute RMSE values for individual organs as compared to total biomass. Total biomass had a RMSE value similar to the CV of measured data. For individual organ, normalized RMSE values were 1.3-3.5 times greater than the CV of measurements (Table 3).

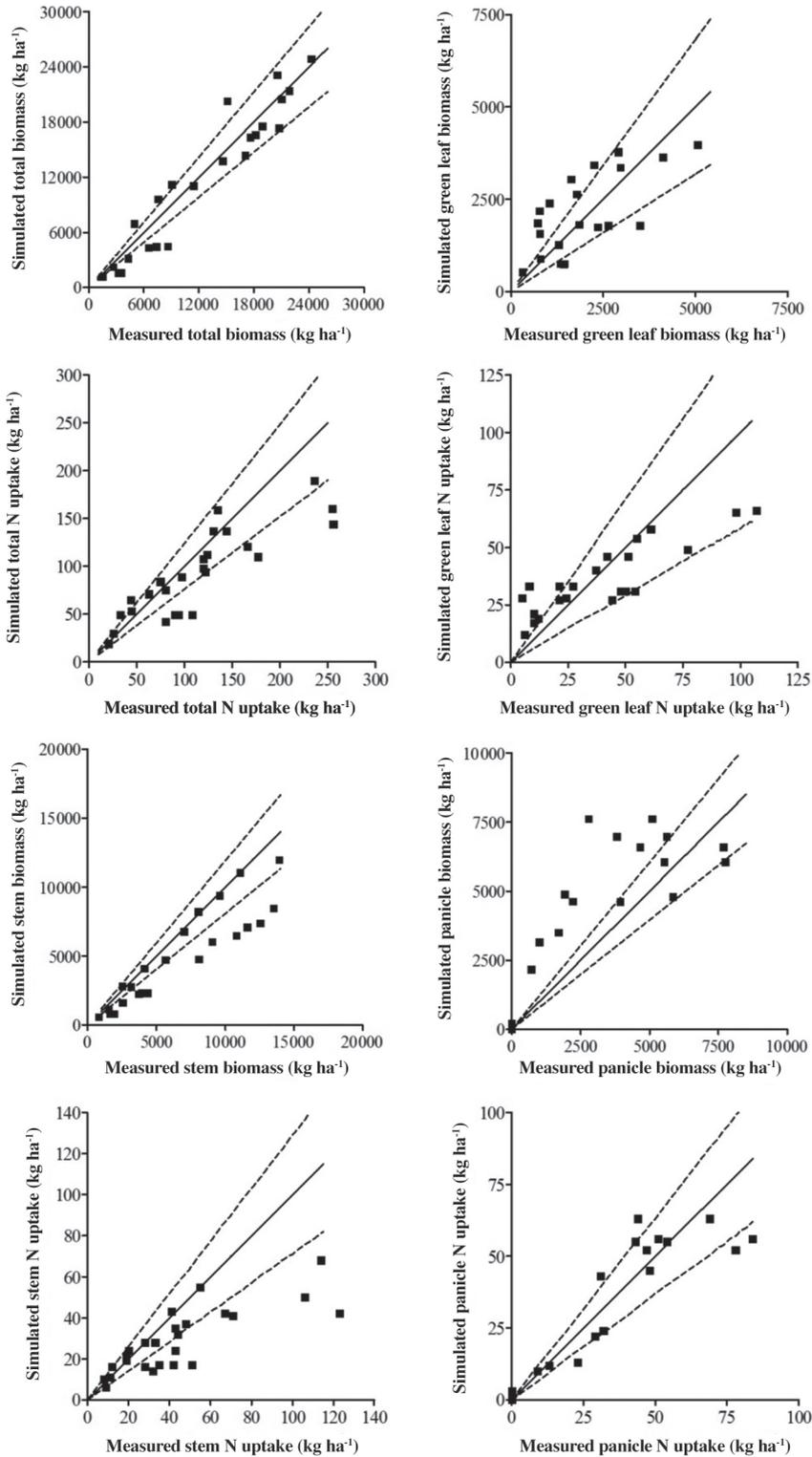
Crop N uptake during the growing season was reproduced acceptably. In graphical comparison, most of the data points fell near the 1:1 line and within the \pm CV lines (Figure 1). Data points falling outside of the \pm CV lines were found mainly below the +CV line, indicating an underestimation specifically for rates above 150 kg N ha⁻¹ (Figure 1). These discrepancies were reflected in their normalized and absolute RMSE values, which were about 50% greater than the CV and SE of measured values, respectively (Table 3). For N uptake of individual organs, there was more spread in the data (Figure 1), which was reflected in higher normalized RMSE values as compared to crop N uptake (Table 3). For these variables, normalized RMSE values were 1.4-2.0 times higher than the CV of measurements. Absolute RMSE values were 1.4-4.8 times greater than the SE of measurements.

Figure 2 shows simulated and measured values of crop biomass, crop N uptake and grain yield at the end of the season, for the independent validation data set. Simulated and measured final crop N uptake and grain yield matched quite well, with the majority of data points close to the 1:1 line and within the \pm CV lines. The *t*-test showed that the simulated values were

similar to measured values within a 95% confidence interval ($P(t) = 0.355$ for crop N uptake and $P(t) = 0.438$ for grain yield). Normalized RMSE values were the lowest among all variables (Table 3). For final crop N uptake and yield, normalized RMSE values were of the same order of magnitude as the CV of measured data, and the absolute RMSE values were two times greater than the SE of measured data. For final crop biomass, the normalized and absolute RMSE values were two and three times greater than the CV and SE of measured data, respectively. Moreover, the *t*-test indicated significant differences between simulated and measured values ($P(t) = 0.008$) and the graphical comparison showed a overestimation of this variable (Figure 2).

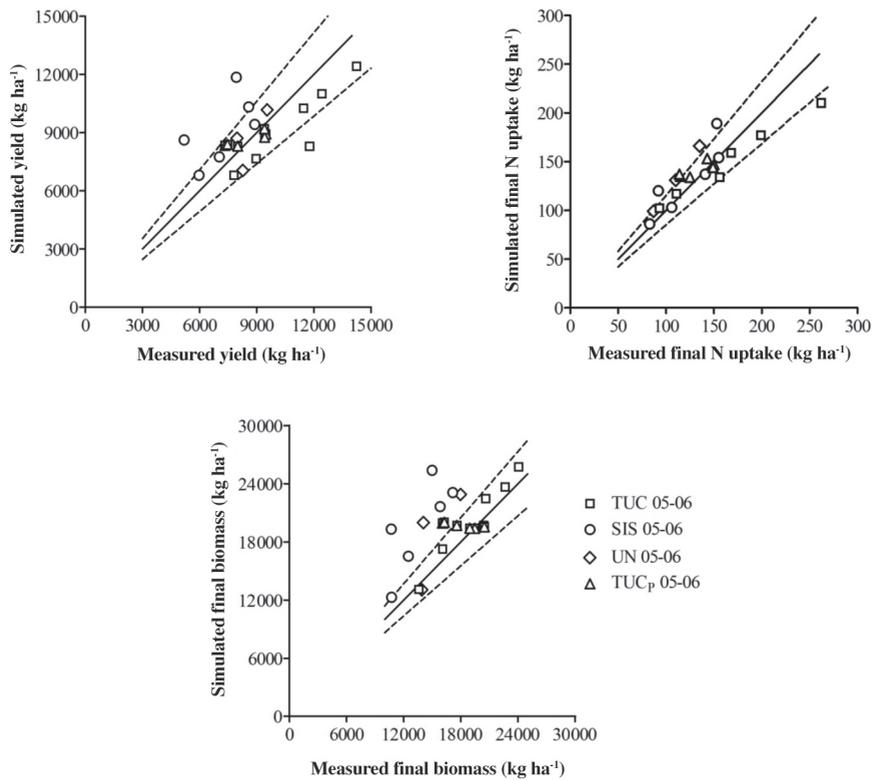
Application of ORYZA2000 model

The cumulative probability curves for potential yields and for grain yield at different N rates and indigenous soil N supply (SOILSP), both simulated using 100-years of synthetic weather data, are shown in Figure 3. Mean values of grain yields simulated respectively for the 0, 100, 200, and 300 kg N ha⁻¹ rates were 4646, 6423, 7740, and 8742 kg ha⁻¹ using an SOILSP of 0.5 kg N ha⁻¹ d⁻¹; and 5534, 7281, 8371, and 9227 kg ha⁻¹ using an SOILSP of 0.65 kg N ha⁻¹ d⁻¹. Across N rates, the simulated grain yields with a SOILSP of 0.65 kg N ha⁻¹ d⁻¹ were, on average, 12% higher than those with 0.5 kg N ha⁻¹ d⁻¹. ORYZA2000 simulated similar grain yield trends at both SOILSP values, predicting higher grain yields with increasing N fertilization (Figure 3). It can also be drawn from Figure 3 that N fertilizer application was justified by an important increase in yield, even at rates as high as 300 kg ha⁻¹. This increase in yield could be obtained using less N fertilizer in the presence of higher indigenous soil N supply. However, even at high N rates (> 200 kg N ha⁻¹) there were significant probabilities of grain yields lower than the attainable yield in the studied area (close to 8700 kg ha⁻¹, Alvarado, 2005). These probabilities for the 0.5 and 0.65 kg N ha⁻¹ d⁻¹ values of SOILSP were, respectively, 95 and 55% for the 200 kg N ha⁻¹ rate and 30 and 16% for the 300 kg N ha⁻¹ rate. Simulated potential yields had a mean value of 10 233 kg ha⁻¹, and the corresponding interannual variability due to climatic conditions was moderate (CV = 15%). However this was higher than yield variability across fertilized treatments and SOILSP values (mean CV = 12%).



Solid lines correspond to the 1:1 relationships; dotted lines correspond to \pm CV of measured variables around the 1:1 line.

Figure 1. Simulated versus measured biomass and N uptake of total aboveground dry matter, green leaves, stems, and panicles throughout the growing season for the calibration data set (2006-2007 season).



Validation set: TUC 05-06, SIS 05-06, UN 05-06, TUC_p 05-06.

Solid lines correspond to the 1:1 relationships; dotted lines correspond to \pm CV of measured variables around the 1:1 line.

Figure 2. Simulated versus measured grain yield, crop N uptake and crop biomass at the end of the season for the validation data set (2005-2006 season).

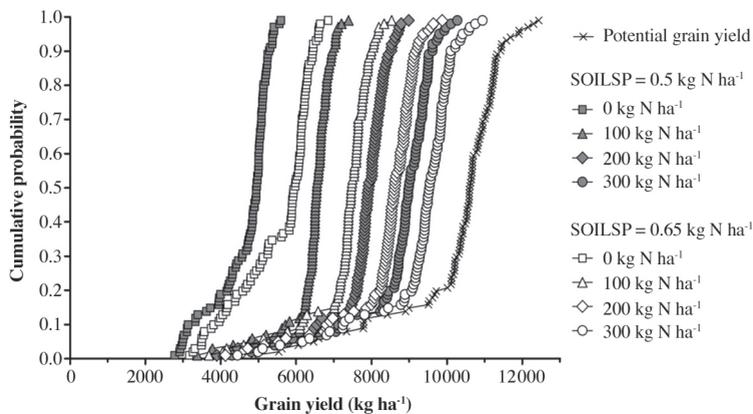


Figure 3. Cumulative probability curves for simulated grain yields under potential production conditions and for simulated grain yields under four fertilization rates in combination with two indigenous soil N supply levels (SOILSP).

DISCUSSION

Evaluation of ORYZA2000 indicated that the reproduction of crop variables at the end of the season was more accurate than the simulation throughout the growing season, as reflected by lower normalized RMSE values (Table 3). Final crop N uptake was simulated with an absolute RMSE of 20 kg ha⁻¹, and a normalized RMSE of 15%, whereas grain yield was simulated with an absolute RMSE of 1666 kg ha⁻¹ and a normalized RMSE of 19%. The normalized RMSE values for final crop N uptake and grain yield were of the same order of magnitude as the CV of measured data, which means that the variable prediction by the model and data measurement were equally accurate. The evaluation results for final crop N uptake were comparable to those for a japonica cultivar growing in Southeast China (Jing *et al.*, 2007). However, the evaluation results for grain yield indicated a lower accuracy. Final crop biomass was simulated with absolute and normalized RMSE values of 4214 kg ha⁻¹ and 25%, respectively. The reproduction of biomass and N uptake of individual organs throughout the season was poor, as reflected by large normalized RMSE values (> 35%; Table 3). Panicle and green leaf biomass were overestimated by the model. However, the total biomass simulation was approximately balanced due to the underestimation of stem dry weight. Therefore, the model predicted total biomass throughout the growing season reasonably well with an absolute RMSE of 2161 kg ha⁻¹ and a normalized RMSE of 19%. In contrast, crop N uptake throughout the growing season was simulated with a low accuracy (absolute RMSE = 41 kg ha⁻¹; normalized RMSE = 36%; Table 3).

Despite of the large panicle biomass overestimation, simulated and measured grain yield at the end of the season matched quite well (absolute and normalized RMSE of 1282 kg ha⁻¹ and 25%, respectively; $P(t) = 0.08$; data not shown). This suggests inaccuracies in spikelet sterility simulation, which is calculated by the model based on the sum of cooling degree-days around the flowering time. According to the ORYZA2000 calculation procedure, spikelet sterility varied from 70 to 87% for the season studied (2006-2007). However, experimental data showed much lower spikelet sterility levels (< 44% between 150 and 300 kg N ha⁻¹ rates, and < 10% for rates below 150 kg N ha⁻¹; data not shown). Clearly, the simulation of this parameter in temperate climates could be improved by including other factors, such as the interaction of N application and low temperatures as it affects spikelet sterility (Gunawardena and Fukai, 2005).

Despite these problems, ORYZA2000 was sufficiently accurate to simulate grain yield and crop N uptake at the

end of the season. Therefore, the model can be applied with confidence to perform rice yield forecasting. In this context, the model was applied to explore potential yields and grain yield response to N fertilization under likely weather conditions in the Parral area. This study confirmed the existence of a yield gap between potential and actual yields. Mean value of simulated potential yields (10 233 kg ha⁻¹) exceeded the attainable yield for cv. Diamante-INIA in the same agroecological area (close to 8700 kg ha⁻¹; Alvarado, 2005). ORYZA2000 predicted potential yields as high as 11 000-12 000 kg ha⁻¹ in 30% of the simulation years (Figure 3), which are similar to yields obtained in field trials developed under potential production conditions in the same area (Alvarado, 2005). However, a high probability of yields lower than the attainable yield was noted, even at high N rates (Figure 3). There was also a high probability that this attainable yield was exceeded (1 - cumulative probability; data not shown). This means that the actual N-recommendation system used in Chile based on predefined "attainable" yield (Rodríguez *et al.*, 2001), should be reviewed in order to avoid excessive N applications or yield reductions due to N limitations. Clearly, there is a need to incorporate dynamic N management. Such an approach combines a moderate basal N rate with variable N rates and distribution within the season, based on indicators of actual crop N status (e.g. chlorophyll meter or leaf color chart). For this purpose, the use of a crop simulation model calibrated under specific production conditions of the major rice-producing area in Chile can help to support experiments for evaluation and adjustment of N management practices.

CONCLUSIONS

We conclude that ORYZA2000 was sufficiently accurate to simulate grain yield and crop N uptake at the end of the season for a japonica rice cultivar growing under N-limited conditions in an irrigated Mediterranean environment. Additional comparisons between model simulations and experimental measurements are required to increase the confidence in the model predictions, particularly for biomass production and N uptake of individual organs.

The long-term simulation study confirmed that potential yield in the Parral area is as high as 12 000 kg ha⁻¹ and that there is a scope for yield increase through improved management practices. Furthermore, a yield response to N fertilization was predicted even at N rates of 300 kg ha⁻¹. However, analyzing the distribution of the simulated grain yield revealed a significant probability of grain yields lower than the attainable yield in this agroecological area, encouraging the need to move from fixed to dynamic N management. In this context, the use

of the ORYZA2000 model, calibrated and evaluated with regard to the production conditions of the major rice-producing area in Chile can support experiments for the evaluation and adjustment of N management practices. The ORYZA2000 model could also support potential production and yield forecasting studies.

ACKNOWLEDGEMENTS

The authors acknowledge the contribution of Dr. B.A.M. Bouman from the International Rice Research Institute in the evaluation of the ORYZA2000 model. This work was supported by the "Programa de Desarrollo de Proveedores Empresas Tucapel – Pontificia Universidad Católica de Chile".

RESUMEN

Evaluación del modelo de crecimiento de arroz ORYZA2000 bajo condiciones limitadas de nitrógeno en un ambiente mediterráneo regado. ORYZA2000 es un modelo para arroz tropical regado desarrollado por el Instituto Internacional de Investigación en Arroz y Universidad de Wageningen, que ha sido evaluado en un amplio rango de ambientes. Sin embargo, los reportes para cultivares japónica creciendo en ambientes templados son escasos. En este estudio, ORYZA2000 fue calibrado y evaluado usando datos de experimentos realizados en el centro-sur de Chile, que incluyeron una variedad japónica cultivada bajo un ambiente Mediterráneo regado, y varias dosis de N. Posteriormente ORYZA2000 fue aplicado para explorar rendimientos potenciales y respuesta en rendimiento a la fertilización N bajo probables condiciones climáticas de la principal zona arrocera de Chile. ORYZA2000 fue suficientemente preciso en simular rendimiento de grano y absorción de N del cultivo al final de la estación. La absorción de N del cultivo fue simulada con una raíz del cuadrado medio del error (RMSE) de 20 kg ha⁻¹ (15%) y el rendimiento de grano con una RMSE de 1666 kg ha⁻¹ (19%). La predicción de biomasa y absorción de N de órganos individuales durante la estación fue pobre. El estudio de simulación a largo plazo confirmó un rendimiento potencial tan alto como 12 000 kg ha⁻¹ en Parral, y la existencia de un margen para incrementar los rendimientos. La respuesta en rendimiento a la fertilización N fue predicha aún a dosis de 300 kg ha⁻¹, aunque también se observó una probabilidad significativa de bajos rendimientos. Este hecho apoya la necesidad de incorporar un manejo dinámico del N en la producción arrocera chilena.

Palabras clave: Modelo ORYZA2000, arroz regado, nitrógeno, ambiente mediterráneo, Chile.

LITERATURE CITED

- Aggarwal, P.K., N. Kalra, S. Chander, and H. Pathak. 2006. InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agricultural Systems* 89:1-25.
- Alvarado, J.R. 2005. Mejoramiento genético del arroz en Chile. Informativo Agropecuario Bioleche-INIA Quilamapu 116. Available at <http://www.inia.cl/medios/quilamapu/pdf/bioleche/BOLETIN116.pdf> (accessed January 2009).
- Alvarado, J.R., and L. Hernaiz. 2005. Ámbar-INIA, nuevo cultivar de arroz de grano corto y muy bajo contenido de amilosa. *Agricultura Técnica* 65:101-104.
- Alvarado, J.R., and A. Pino. 1982. Arroz Diamante-INIA. *Agricultura Técnica* 42:253.
- Arora, V.K. 2006. Application of a rice growth and water balance model in an irrigated semi-arid subtropical environment. *Agricultural Water Management* 83:51-57.
- Belder, P., B.A.M. Bouman, and J.H.J. Spiertz. 2007. Exploring options for water savings in lowland rice using a modelling approach. *Agricultural Systems* 92:91-114.
- Boling, A.A., B.A.M. Bouman, T.P. Tuong, M.V.R. Murty, and S.Y. Jatmiko. 2007. Modelling the effect of groundwater depth on yield-increasing interventions in rainfed lowland rice in Central Java, Indonesia. *Agricultural Systems* 92:115-139.
- Bouman, B.A.M., M.J. Kropff, T.P. Tuong, M.C.S. Wopereis, H.F.M. ten Berge, and H.H. van Laar. 2001. ORYZA2000: Modelling lowland rice. 235 p. International Rice Research Institute, Los Baños, Philippines, Wageningen University and Research Centre, Wageningen, The Netherlands.
- Bouman, B.A.M., and H.H. van Laar. 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agricultural Systems* 87:249-273.
- Carreres, R., J. Sendra, R. Ballesteros, and J. García de la Cuadra. 2000. Effects of pre-flood nitrogen rate and mid-season nitrogen timing on flooded rice. *Journal of Agricultural Science* 134:379-390.
- Casanova, D., J. Goudriaan, and A.D. Bosch. 2000. Testing the performance of ORYZA1, an explanatory model for rice growth simulation, for Mediterranean conditions. *European Journal of Agronomy* 12:175-189.
- CIREN. 1994. Descripciones de suelos, materiales y símbolos: estudio agrológico VIII Región. 288 p. Centro de Investigación de Recursos Naturales (CIREN), Santiago, Chile.

- CIREN. 1997. Descripciones de suelos, materiales y símbolos: estudio agrológico VII Región. 161 p. Centro de Investigación de Recursos Naturales (CIREN), Santiago, Chile.
- Fageria, N.K., and V.C. Baligar. 2001. Lowland rice response to nitrogen fertilization. *Communications in Soil Science and Plant Analysis* 32:1405-1429.
- Feng, L., B.A.M. Bouman, T.P. Tuong, R.J. Cabangon, Y. Li, G. Lu, and Y. Feng. 2007. Exploring options to grow rice using less water in northern China using a modelling approach. I. Field experiments and model evaluation. *Agricultural Water Management* 88:1-13.
- Gunawardena, T.A., and S. Fukai. 2005. The interaction of nitrogen application and temperature during reproductive stage on spikelet sterility in field-grown rice. *Australian Journal of Agricultural Research* 56:625-636.
- Haefele, S.M., M.C.S. Wopereis, M.K. Ndiaye, and M.J. Kropff. 2003. A framework to improve fertilizer recommendations for irrigated rice in West Africa. *Agricultural Systems* 76:313-335.
- Jing, Q., B.A.M. Bouman, H. Hengsdijk, H. Van Keulen, and W. Cao. 2007. Exploring options to combine high yields with high nitrogen use efficiencies in irrigated rice in China. *European Journal of Agronomy* 26:166-177.
- Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, *et al.* 2003. The DSSAT cropping system model. *European Journal of Agronomy* 18:235-265.
- Meza, F.J., D.S. Wilks, S.J. Riha, and J.R. Stedinger. 2003. Value of perfect forecasts of sea surface temperature anomalies, for selected rain-fed agricultural locations of Chile. *Agricultural and Forest Meteorology* 116:117-135.
- O'Leary, G.J., and D.J. Connor. 1998. A simulation study of wheat crop response to water supply, nitrogen nutrition, stubble retention, and tillage. *Australian Journal of Agricultural Research* 49:11-19.
- Peng, S., and K.G. Cassman. 1998. Upper thresholds of nitrogen uptake rates and associated nitrogen fertilizer efficiencies in irrigated rice. *Agronomy Journal* 90:178-185.
- Richardson, C.W. 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resources Research* 17:182-190.
- Rodríguez, J., D. Pinochet, and F. Matus. 2001. Fertilización de los cultivos. 117 p. LOM Ediciones, Santiago, Chile.
- Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-Wheat. *Agronomy Journal* 96:615-630.
- Segda, Z., S.M. Haefele, M.C.S. Wopereis, M.P. Sedogo, and S. Guinko. 2005. Combining field and simulation studies to improve fertilizer recommendations for irrigated rice in Burkina Faso. *Agronomy Journal* 97:1429-1437.
- Soundharajan, B., and K.P. Sudheer. 2009. Deficit irrigation management for rice using crop growth simulation model in an optimization framework. *Paddy Water Environment* 7:135-149.
- Stöckle, C.O., M. Donatelli, and R. Nelson. 2003. CropSyst, a cropping systems simulation model. *European Journal of Agronomy* 18:289-307.
- Tang, L., Y. Zhu, D. Hannaway, Y. Meng, L. Liu, L. Chen, and W. Cao. 2009. RiceGrow: A rice growth and productivity model. *NJAS-Wageningen Journal of Life Sciences* 57:83-92.
- van Ittersum, M.K., P.A. Leffelaar, H. van Keulen, M.J. Kropff, L. Bastiaans, and J. Goudriaan. 2003. On approaches and applications of the Wageningen crop models. *European Journal of Agronomy* 18:201-234.
- Xue, C.Y., X.G. Yang, B.A.M. Bouman, L.P. Feng, H.H. van Laar, H.Q. Wang, *et al.* 2005. Preliminary approach on adaptability of ORYZA2000 model for aerobic rice in Beijing region. *Acta Agronomica Sinica* 31:1567-1571.
- Zhang X., J.H. Lee, Y. Abawi, Y. Kim, D. McClymont, and H.D. Kim. 2007. Testing the simulation capability of APSIM-ORYZA under different levels of nitrogen fertiliser and transplanting time regimes in Korea. *Australian Journal of Experimental Agriculture* 47:1446-1454.