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Testing the simulation capability of APSIM-ORYZA under different levels of nitrogen fertiliser and transplanting time regimes in Korea

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Abstract. APSIM-ORYZA is a new functionality developed in the APSIM framework to simulate rice production while addressing management issues such as fertilisation and transplanting, which are particularly important in Korean agriculture. To validate the model for Korean rice varieties and field conditions, the measured yields and flowering times from three field experiments conducted by the Gyeonggi Agricultural Research and Extension Services (GARES) in Korea were compared against the simulated outputs for different management practices and rice varieties. Simulated yields of early-, mid- and mid-to-late-maturing varieties of rice grown in a continuous rice cropping system from 1997 to 2004 showed close agreement with the measured data. Similar results were also found for yields simulated under seven levels of nitrogen application. When different transplanting times were modelled, simulated flowering times ranged from within 3 days of the measured values for the early-maturing varieties, to up to 9 days after the measured dates for the mid- and especially mid-to-late-maturing varieties. This was associated with highly variable simulated yields which correlated poorly with the measured data. This suggests the need to accurately calibrate the photoperiod sensitivity parameters of the model for the photoperiod-sensitive rice varieties in Korea.

Additional keywords: rice, systems modelling

Introduction

Rice is an important crop in Korea and is a staple in the diet of the Korean people. In Korean agriculture, over 90% of rice is transplanted and it is common to apply additional nitrogen to maintain high yields (Chung *et al*. 2003; Choe *et al*. 1998). Surveys have found that Korean rice growers tend to over-apply nitrogen to their paddy fields (Chung *et al*. 2003; Cho *et al*. 2001*a*) and the excessive nitrogen has resulted in crop-loss from pests, diseases and the contamination of surface and groundwater storages (Cho *et al*. 2001*b*). In addition, some rice varieties grown in Korea are photoperiod sensitive, thus transplanting times and prevailing weather conditions during the photoperiod-sensitive phase (from the end of basic vegetative to panicle initiation) influence flowering times and yield. Therefore, the optimal transplanting time is a key management variable for growers.

In the past, intensive factorial field trials have been conducted at the Gyeonggi Agricultural Research and Extension Services (GARES), Korea, to determine the optimal levels of nitrogen and transplanting times for various varieties. However, the results are site-specific and are influenced by specific environmental and management conditions in a limited number of experiments. Therefore, there is a need to extrapolate these experimental results to include the temporal effects of weather and to account for different management practices and soil types.

Rice-based simulation models offer the potential to achieve these objectives to identify production constraints and design optimal management regimes relating to nitrogen application and transplanting times. They can improve research efficiency by allowing the analysis of system performance on different soils, varying season lengths and rice varieties (Keating *et al*. 1999; Lisson *et al*. 2000; Robertson *et al*. 2002). One such model is ORYZA2000, which was developed as a successor to the RICEMOD and MACROS rice growth models (Bouman *et al*. 2001), with the addition of irrigation and nitrogen fertiliser management capabilities. Bouman and van Laar (2006) used ORYZA2000 to simulate rice production in the Philippines with satisfactory results. However, in their study, rice yields were simulated in a single season as ORYZA2000 is only a single-crop and single-season model.

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To overcome these limitations, the APSIM-ORYZA model has been developed (Zhang *et al*. 2004) for the APSIM framework (Keating *et al*. 2003) based upon the original ORYZA2000 model. Key objectives of the model are to accurately simulate the growth and development of rice while also dealing with key management decisions such as fertilisation, transplanting times and field management practices. It allows rice physiology such as photosynthesis, phenological development and yield to be simulated as intended in ORYZA2000 while using the existing APSIM suite of modules for water, nitrogen and other soil processes and management issues. This systems-capability allows the investigation of a continuous cropping system, carry-over effects and field management decisions.

To date, the capability of the APSIM-ORYZA model to simulate a long-term crop rotation system has not been tested. Additionally, modelling the nitrogen components has been limited to the initial study by Zhang *et al*. (2004) which used a pre-existing APSIM nitrogen module developed for dryland conditions. The nitrogen dynamics including transformation and translocation in reduced layers which happen particularly in paddy soils are different from those in dryland soil conditions (Godwin and Singh 1998). An alternative approach is to use the simple book-keeping approach describing the soil nitrogen

Table 1. Description of three experiments conducted by Gyeonggi Agricultural Research and Extension Services (GARES), Korea
Datasets derived from these experiments were used to evaluate the APSIM-ORYZA model's performance in this study

Variety	Treatment	Sowing	Transplanting	Fertilisation	Duration	Field management
				Experiment 1		
'Odaebyeo'	Continuous rice cropping system	15 April	20 May	55 kg N/ha on 20 May; 33 kg N/ha on 4 June (22 kg N/ha after 1999); 22 kg N/ha on 6 July (33 kg N/ha after 1999)	1997–2004	5-cm high stubble and roots left in field; irrigation to keep at least 0.5 cm pond depth; chemicals applied to kill weeds, pests and diseases if necessary.
'Hwaseongbyeo'				55 kg N/ha on 20 May; 33 kg N/ha on 4 June (22 kg N/ha after 1999); 22 kg N/ha on 16 July (33 kg N/ha after 1999)		
'Chucheongbyeo'				55 kg N/ha on 20 May; 33 kg N/ha on 4 June (22 kg N/ha after 1999); 22 kg N/ha on 26 July (33 kg N/ha after 1999)		
				Experiment 2		
'Odaebyeo'	Different rates of of N application: 0, 50, 70, 90, 110, 140, 170 kg N/ha	1 May	31 May	0, 25, 35, 45, 55, 70 or 85 kg N/ha on 31 May; 0, 10, 14, 18, 22, 28 or 34 kg N/ha on 14 June; 0, 15, 21, 27, 33, 42 or 51 kg N/ha on 11 July	2003, 2004, 2005 (mid-to-late-maturingvariety only)	Same as above
'Hwaseongbyeo'				0, 25, 35, 45, 55, 70 or 85 kg N/ha on 31 May; 0, 10, 14, 18, 22, 28 or 34 kg N/ha on 14 June; 0, 15, 21, 27, 33, 42 or 51 kg N/ha on 21 July		
'Chucheongbyeo'				0, 25, 35, 45, 55, 70 or 85 kg N/ha on 31 May; 0, 10, 14, 18, 22, 28 or 34 kg N/ha on 14 June; 0, 15, 21, 27, 33, 42 or 51 kg N/ha on 31 July		
				Experiment 3		
'Odaebyeo'	Different trans-planting times: 10 May, 20 May, 30 May, 9 June	10 April, 20 April, 30 April, 10 May	10 May, 20 May, 30 May, 9 June	55 kg N/ha on 10 May, 20 May, 30 May or 9 June; 22 kg N/ha on 24 May, 3 June, 13 June or 23 June; 33 kg N/ha on 28 June, 4 July, 11 July or 20 July	2002, 2003, 2004, 2005 (mid-to-late-maturing variety only)	Same as above
'Hwaseongbyeo'				55 kg N/ha on 10 May, 20 May, 30 May or 9 June; 22 kg N/ha on 24 May, 3 June, 13 June or 23 June; 33 kg N/ha on 12 July, 16 July, 24 July or 28 July		
'Chucheongbyeo'				55 kg N/ha on 10 May, 20 May, 30 May or 9 June; 22 kg N/ha on 24 May, 3 June, 13 June or 23 June; 33 kg N/ha on 24 July, 27 July, 31 July or 4 August		

supply used in the ORYZA2000 model (Bouman *et al*. 2001). Bouman and van Laar (2006) tested this approach using Philippines-based data and reported satisfactory results for paddy soils. However, this approach had not been tested in other environments where the soil and climate are different, such as in Korea. In addition, some Korean rice varieties are photoperiod sensitive whereby daylength during the photoperiod-sensitive phase has significant impacts on the flowering time (Choi *et al*. 2002; Lee *et al*. 2001; Kim *et al*. 1998*a*; Kim *et al*. 1998*b*). In this study, the photoperiod-sensitivity parameter values specific for Korean rice varieties were not available, so the parameter values describing the non-photoperiod-sensitive rice varieties in ORYZA2000 model (Bouman *et al*. 2001) were adapted for the model. Testing whether these parameter values can adequately simulate the photoperiod-sensitivity characteristics of the Korean varieties under different transplanting time regimes is another aim of this paper.

Three sets of data derived from field experiments conducted at GARES in south Korea were used to test the model's performance by simulating rice production in a long-term rotation system, and through varying management issues such as nitrogen fertiliser applications and transplanting times, which are critical decisions for successful rice production in Korea. Several statistical criteria were used to evaluate the goodness-of-fit between the simulated and measured outputs.

Materials and methods

Experiments

Three experiments were conducted in neighbouring plots at the Gyeonggi Agricultural Research and Extension Services (GARES), Korea, with three rice varieties: 'Odaebyeo', an early-maturing variety (photoperiod-insensitive), 'Hwaseongbyeo', a mid-maturing variety (photoperiod-sensitive) and 'Chucheongbyeo', a mid-to-late-maturing variety (photoperiod-sensitive). The first experiment was designed to investigate rice production in a normal-transplanting and continuous rice cropping system from 1997 to 2004. The second experiment was designed to investigate rice yields under seven levels of nitrogen application. The experiment was conducted with all three varieties in 2003 and 2004 but only with the mid-to-late-maturing variety in 2005. The third experiment was designed to investigate the impact of transplanting time on rice yield. The experiment was carried out with all three varieties in 2002, 2003 and 2004 but only with the mid-to-late-maturing variety in 2005. These experiments are summarised in Table 1.

Description of the APSIM-ORYZA model

The key features of the APSIM-ORYZA model including its input requirements, interactions with other components of APSIM (e.g. APSIM-Eo, APSIM-SoilWat2, APSIM-Irrigate and APSIM-Fertiliz, see Keating *et al*. 2003) and outputs have been described in Zhang *et al*. (2004). Briefly, APSIM-ORYZA simulates rice phenology, leaf area development, biomass production, yield and nitrogen accumulation in response to environmental variables such as temperature, solar radiation, soil water and nitrogen. Water availability was simulated via the APSIM-SoilWat2 module while crop water requirement, which is based upon potential evapotranspiration, was computed in the APSIM-Eo module. Fertilisation and irrigation management were simulated via the APSIM-Fertiliz and APSIM-Irrigate modules. The APSIM framework also includes a nitrogen and carbon dynamics module 'soilN', but the physical and chemical processes that it describes are based upon dryland conditions rather than paddy soils. In this study, a simple book-keeping routine for simulating the nitrogen balance from the soil and fertilisers was used, based upon a similar method developed for paddy soils in the Philippines (Bouman *et al*. 2001). The soil profile including the root zone was considered a single layer and a constant 'indigenous soil nitrogen' parameter (e.g. 0.8 kg/ha) represented the mineral nitrogen pool. In the ORYZA2000 model, this indigenous soil nitrogen supply was interpreted as the potential daily nitrogen supply for uptake by the crop. The pool was balanced on a daily basis by adding the mineral nitrogen from the applied fertiliser which was calculated as the

Table 2. Input variables and parameters for key physiological processes simulated in APSIM-ORYZA and their calibration status

Simulation	Input variables and parameters	Source	Module
Phenology	Meteorological data: daily max. and min. temp, rainfall, solar radiation	Time-series record at Gyeonggi Agricultural Research and Extension Services (GARES), Korea	'Oryza' module in APSIM
	Variety-specific development constant	The four parameters have been calibrated for each Korean variety using data from an experiment from 1993 to 1996	
CO_2 assimilation and yield formation	Extinction coefficients for visible light; initial light-use efficiency of a single leaf; parameters for C partition among organs; N distribution in the canopy; spikelet formation factor etc.	Default values from ORYZA2000 model	'Oryza' module in APSIM
Soil water balance balance and soil nitrogen supply	Potential evapotranspiration	Default values in APSIM	'EO' module in APSIM
	Water availability in soil profile	Default values in APSIM	'SoilWat2' module in APSIM
	Soil nitrogen supply	The indigenous soil N supply was determined by field experiment at GARES, Korea; recovery coefficient of N fertiliser was the default value in ORYZA2000 model	'Bookkeeping' N routine in ORYZA2000 model
Irrigation, fertilisation and other field management	Irrigation (depth of ponding water), application levels of N fertiliser and transplanting dates	Recorded values from field experiment at GARES, Korea	'Irrigate', 'Fertiliz', 'Manager' and 'APsoil' modules in APSIM

product of the fertiliser application rate and the recovery coefficient (Cassman *et al*. 1996; Bouman *et al*. 2001). Bouman and van Laar (2006) suggested that both the indigenous soil nitrogen parameter and the fertiliser recovery coefficient should be calibrated if the approach is to be applied to other soils and conditions. In this study, the indigenous soil nitrogen supply was determined by a 'trial and error' method to simulate the rice yield in a zero nitrogen field. However, the fertiliser recovery coefficient could not be calibrated due to a lack of field measurements including nitrogen uptake by the crop. Therefore, the default value of this parameter from the ORYZA2000 model was used in this study.

Input data and simulation configuration

Daily meteorological data including solar radiation, maximum and minimum temperatures, precipitation and wind speeds from 1996 to 2005 were collected using an automatic weather station. The soils in the three experiments were clay-loam in texture with similar physical, chemical and hydraulic properties. Soil data including saturated water content, drained upper limit and wilting point were not available, hence the default values from the APSIM database were used (Keating *et al*. 2003; http://www.apsim.info/apsim/, verified 24 October 2007). The error from this assumption would be negligible as the field was fully irrigated with a maximum ponding depth of 100 mm so there was little chance of water stress occurring in the crop. An impermeable clay layer was assumed at a depth of 20 cm below ground level for modelling the irrigation ponding effect. Soil albedo was assumed to be 1.3 for the surface of the rice field (Bouman *et al*. 2001). Soil nitrates, ammonium content, organic mater and pH in each soil layer (9 layers over 120 cm of soil profile) were measured for each experiment to use in the APSIM-Soil module. Total rice residues of 1500 kg/ha remained in the field after harvest with a carbon/nitrogen ratio of 20 : 1 for the residue and 14.5 : 1 for the soil. Irrigation and fertilisation were simulated as a continuous process from 1997 to 2004 using a crop–fallow–crop rotation system. The carry-over effect of nitrogen in the soil profile could not be simulated due to limitations of the nitrogen balance book-keeping routine that was used.

Calibrating the variety-specific parameters was limited to the phenological components (describing the development rate) using data from a similar experiment conducted from 1993 to 1996. Parameter values for the other physiological components describing rice growth and development (such as specific leaf area and partitioning factors of carbohydrate) were sourced from the default values of 'variety IR72' from the ORYZA2000 model (Bouman *et al*. 2001).

Flowering time is an important phenological event for crop management and its accurate prediction is a prerequisite for yield prediction (Lee *et al*. 1999). It is well known that flowering time is strongly affected by the photoperiod and that a short daylength during the photoperiod-sensitive phase accelerates the flowering process and vice versa (Yin *et al*. 1997; Yin and Kropff 1998 and references therein). In the ORYZA2000 model, the photoperiod sensitivity of rice is quantified by a variety-specific factor derived from a non-photoperiod-sensitive variety (IR72). Due to lack of measurements in this study, the default values for IR72 were used.

Irrigation scheduling, transplanting dates and nitrogen application rates used in each simulation are in Table 1. It was assumed that all of the nutrients except nitrogen were optimally provided and crops did not suffer from diseases or pest. In these experiments, measurements of leaf dry weight, leaf area and leaf nitrogen content were not made.

All simulation input variables and parameters, their sources and calibration status and the corresponding simulation modules are in Table 2.

Statistical measures for evaluating model performance

In this study, both a graphical comparison of results and statistical analyses were used to evaluate the model's performance. The statistical measures used included root mean

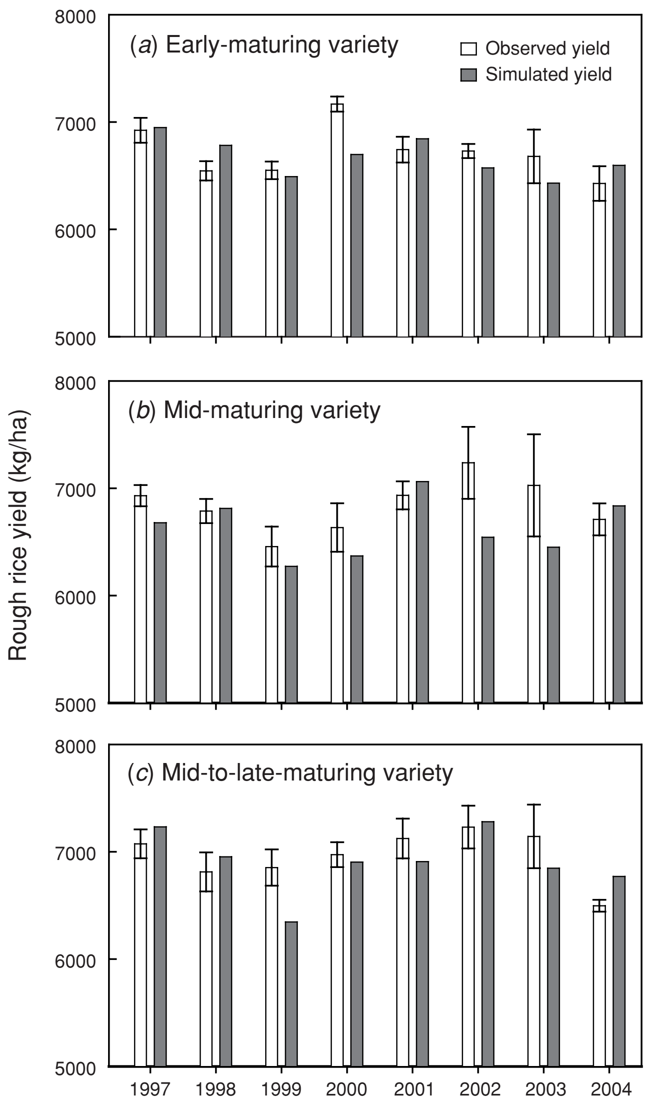

Fig. 1. Simulated and measured yields of (*a*) 'Odaebyeo' (early-maturing variety), (*b*) 'Hwaseongbyeo' (mid-maturing variety) and (*c*) 'Chucheongbyeo' (mid-to-late-maturing variety) grown in the continuous rice cropping system at Hwaseong, Korea, from 1997 to 2004. Vertical bars represent the standard deviation of three replicates of measurements.

square error (*RMSE*) and root mean square percent error (*RMS%E*) as suggested by Mayer and Butler (1993), Yang *et al*. (2000) and Bouman and van Laar (2006). These values were compared with the standard deviation (s.d.) and coefficient of variation (CV) values of the measured data. The *RMSE* and *RMS%E* were calculated as follows:

$$RMSE = \{[\Sigma(Y_m - Y_s)^2]/n\}^{0.5}$$

$$RMS\%E = 100 \times \{[\Sigma(Y_m - Y_s)^2]/n\}^{0.5}/\tilde{Y}_m$$

where Y_m and Y_s are the measured and simulated yields, respectively; n is the number of data pairs; and $\tilde{Y}_m$ is the mean value of the measured yield.

Paired *t*-tests and linear regression analysis were also used to assess the goodness-of-fit between the observed and simulated results using the GENSTAT software (Version 9.2.0.153, VSN International Ltd, Oxford). If the *P*-value from the paired *t*-test was greater than 0.05, it was concluded that no significant differences existed between the measured and simulated values.

Another performance measure used to evaluate the model was the 'efficiency of forecasting' (*EF*) statistic which has been used extensively in this type of study (Loague and Green 1991). The *EF* statistic represents the overall goodness-of-fit of the data (Mayer and Butler 1993) with negative values indicating poor performance of the model, and values close to one representing high performance. *EF* was calculated based upon the methodology of Mayer and Butler (1993):

$$EF = 1 - \Sigma(Y_m - Y_s)^2/\Sigma(Y_m - \tilde{Y}_m)^2$$

Results

APSIM-ORYZA's performance was first evaluated by visually comparing the simulated yields with the measured values (mean ± s.d.) for the three rice varieties (early-, mid- and mid-to-late-maturing) grown in a continuous rice cropping system from 1997 to 2004 (Fig. 1). For the early-maturing variety 'Odaebyeo', the model overestimated yield in 1998 but under-estimated yield in 2000 and 2002. In other years, the simulated yields were within one standard deviation of the measured values (Fig. 1). For the mid-maturing variety 'Hwaeeongbyeo', the simulated yields in 1997, 2000, 2002 and 2003 were lower than the experimental values, but close to the measured values in the remaining years. Yields of the mid-to-late-maturing variety 'Chucheongbyeo' were under-estimated in 1999 and 2004 and overestimated in 1997 and 2004. There was no significant difference in the remaining years.

The statistical outputs used to evaluate the model performance are in Table 3. Paired *t*-test showed no significant differences between the measured and simulated yield values (at P = 0.05 confidence level). The R^2 value from the linear regression was 0.33. The *RMSE* value of simulated yields was 242 kg/ha which is less than the s.d. of the measured yields. The *RMS%E* value of simulated data was 3.5% which is less than the CV of the measured values. The *EF*-value was positive but low at 0.02. All of these indicators suggest that the model performance was acceptable while simulating the production of the three varieties in a continuous rice cropping system over the period from 1997 to 2004.

The capability of model to simulate rice production in a nitrogen-limited environment was tested against data derived from a field experiment with seven levels of nitrogen fertiliser application (Fig. 2). The results show that for the early-maturing variety, the simulated yields in some of the treatments in 2003 (50, 70 and 90 kg N/ha) and 2004 (70, 90, 110, 140 and 170 kg N/ha) were higher than the measured yields. However, in other treatments, they were close to the measured values. For the mid-maturing variety, the model underestimated the yields from two of the treatments in 2003 (50 and 140 kg N/ha) and the 50 kg N/ha treatment in 2004, while overestimating yields from the 140 and 170 kg N/ha treatments in 2004. The simulated yields for the mid-to-late-maturing variety were lower than one s.d. from the measured values from six of the treatments in 2004 and 2005 (0 kg N/ha in 2004, and 0, 50, 70, 90 and 110 kg N/ha in 2005) and higher than one s.d. during three of the treatments in 2003 and 2004 (170 kg N/ha in 2003, and 140 and 170 kg N/ha in 2004). However, the yields under other treatments were within one standard deviation of the measured values. Paired *t*-test results (Table 3) showed that simulated yields of three varieties were not different from the measured data at the 95% confidence level. The R^2 value from the linear regression was 0.76, indicating a close correlation between the simulations and the measurements. The *RMSE* value of simulated yield was less than one s.d. of the measured data and the *RMS%E* value was

Table 3. Values of different statistics (test statistics and difference measures) when assessing differences between the measured and simulated yields in three experiments conducted by Gyeonggi Agricultural Research and Extension Services (GARES), Korea

N, the number of data pairs; Y_m ± s.d., mean of measured yield plus or minus standard deviation of measured yield; CV, coefficient of variation; *Ys* ± s.d., mean of simulated yield plus or minus standard deviation of simulated yield; *P*, probability value of paired *t*-test; α, β and R^2 are the slope, intercept and coefficient of determination of linear regression between the measured and the simulated yield; *RMSE*, root mean square error; *RMS%E*, root mean square percent error; *EF*, efficiency of forecasting

N	Y_m ± s.d.	CV (%)	Y_s ± s.d.	*P*-value	α	β	R^2	*RMSE*	*RMS%E*	*EF*
Experiment 1 (1997–2004, continuous rice cropping system)										
24	6841 ± 250	3.7	6746 ± 259	0.06	0.58	2944	0.33	242	3.5%	0.02
Experiment 2 (nitrogen fertiliser experiment)										
49	6112 ± 897	14.7	6143 ± 1078	0.69	0.73	1628	0.76	515	8.4%	0.66
Experiment 3 (transplanting date experiment)										
40	6883 ± 335	5.1	6743 ± 452	0.06	–0.29	8628	0.13	682	10.3%	–3.25

lower than the CV of the measured data. The *EF*-value was 0.66, indicating a good performance of the model.

The model's ability to simulate flowering times and yields of three varieties under four transplanting dates was assessed by comparing the simulated values with the measured data (Table 3; Fig. 3). For the early-maturing variety, the simulated flowering times (Table 4) were less than 3 days from the observed data. The simulated yields were within one standard deviation of the measured values in all years except those transplanted on 9 June 2002 and 10 May 2003 (Fig. 3). When simulating the flowering time of the mid-maturing variety, the predicted flowering dates were later than the measured dates by up to 8 days. The simulated yields of crops transplanted on 30 May and 9 June 2002, 20 May and 9 June 2003 were different from the measured values although in other transplanting treatments the simulation results were in agreement with the

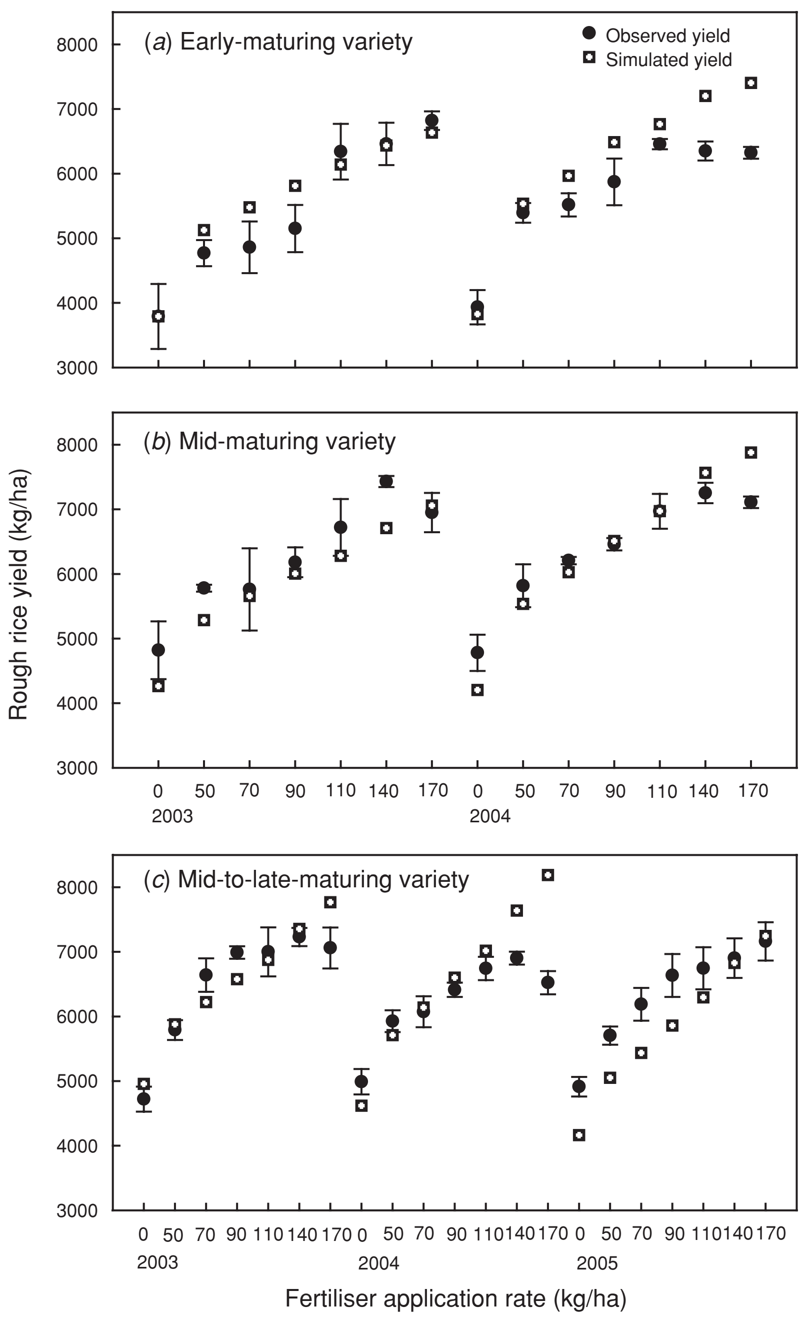

Fig. 2. The simulated and measured rice yields of (*a*) 'Odaebyeo' (early-maturing variety), (*b*) 'Hwaseongbyeo' (mid-maturing variety) and (*c*) 'Chucheongbyeo' (mid-to-late-maturing variety) grown in the field applied with different levels of nitrogen fertiliser. Vertical bars represent the standard deviation of three replicates of measurements.

measurements. For the mid-to-late-maturing variety, the simulated flowering dates were later than the measured flowering dates by up to 9 days (measured flowering dates for 2005 are not available). The simulated yields of rice transplanted on 30 May and 9 June 2002; 10 May, 30 May and 9 June 2003; 10 May and 6 June 2004; 20 May and 9 June 2005 did not match the measured values, although there was agreement in the remaining treatments. The R^2 value from the linear regression between the simulated and the measured values was 0.13. The *RMSE* value of simulated yields was 682 kg/ha which is 104% larger than the s.d. of the measured data. The *RMS%E* value was 10.3% which is 102% larger than CV of the measured data. Furthermore, the *EF*-value was –3.25. Those statistics suggests that there was a large discrepancy between the simulated yields and the measured values and that the performance of the model in this case was unacceptable.

Discussion

The main purpose of developing the APSIM-ORYZA model was to simulate a continuous cropping system incorporating

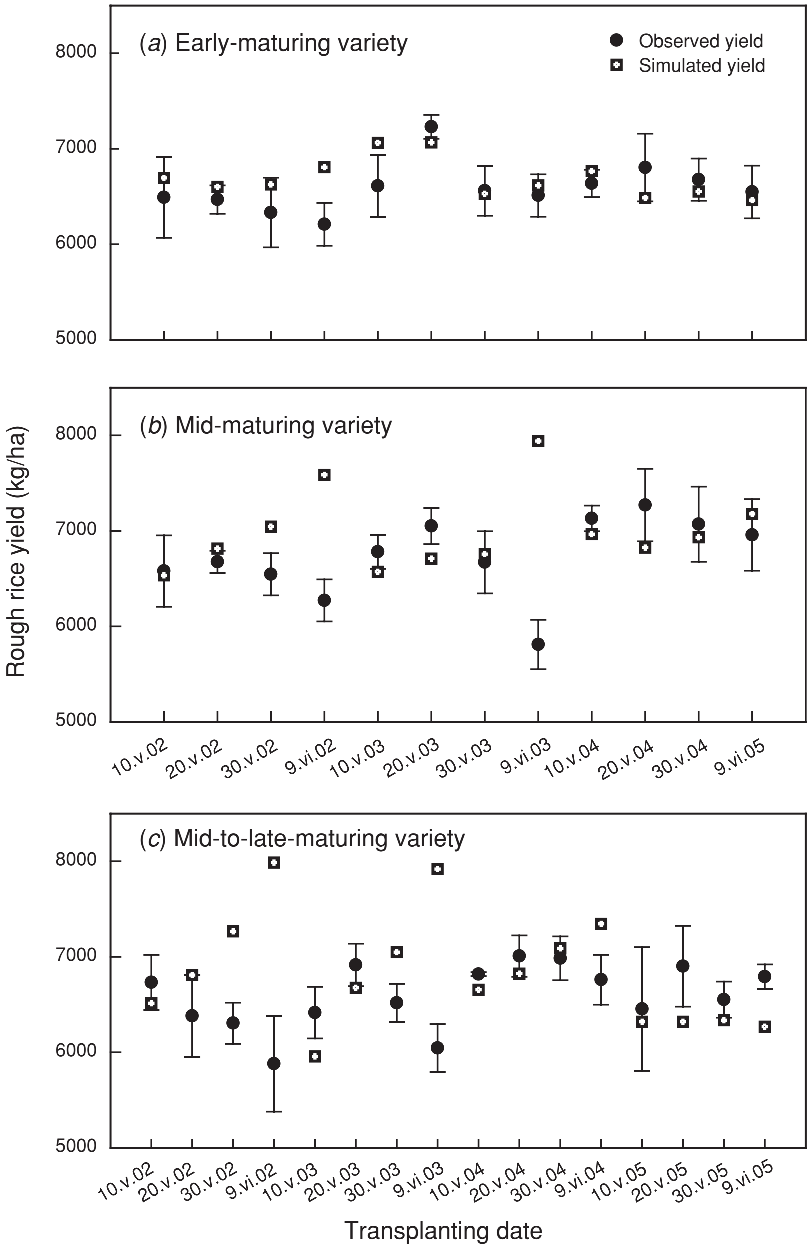

Fig. 3. Simulated and measured rice yields of (*a*) 'Odaebyeo' (early-maturing variety), (*b*) 'Hwaseongbyeo' (mid-maturing variety) and (*c*) 'Chucheongbyeo' (mid-to-late-maturing variety) transplanted to the main field at different dates. Vertical bars represent the standard deviation of three replicates of measurements.

Table 4. Simulated and measured flowering dates of 'Odaebyeo', an early-maturing rice variety (photoperiod insensitive); 'Hwaseongbyeo', a mid-maturing rice variety (photoperiod sensitive); and 'Chucheongbyeo', a mid-to-late-maturing rice variety (photoperiod sensitive) when transplanted at four different times

Transplanting date	Early-maturing variety		Mid-maturing variety		Mid-to-late-maturing variety	
	Measured	Simulated	Measured	Simulated	Measured	Simulated
10 May 2002	25 July	26 July	3 August	7 August	15 August	17 August
20 May 2002	29 July	29 July	9 August	11 August	19 August	22 August
30 May 2002	4 August	4 August	16 August	17 August	26 August	28 August
9 June 2002	14 August	12 August	24 August	26 August	2 September	6 September
10 May 2003	23 July	25 July	6 August	7 August	18 August	18 August
20 May 2003	29 July	30 July	10 August	12 August	21 August	22 August
30 May 2003	5 August	5 August	18 August	18 August	25 August	26 August
9 June 2003	14 August	12 August	22 August	25 August	29 August	5 September
10 May 2004	23 July	26 July	4 August	6 August	14 August	16 August
20 May 2004	27 July	29 July	8 August	10 August	16 August	20 August
30 May 2004	5 August	3 August	13 August	15 August	20 August	26 August
9 June 2004	9 August	10 August	15 August	23 August	25 August	3 September

different field management practices over a long-term period (Zhang *et al*. 2004). However, in the current version of the APSIM framework, the module for soil nitrogen dynamics was designed only for dryland soils and has proven to be unsuitable for the paddy soils under investigation (Zhang *et al*. 2004). Due to the inability to simulate soil nitrogen dynamics by the simple book-keeping routine that was used in this study, the carry-over effect of soil nitrogen in a continuous system could not be simulated. However, water balance and management of ponding were continuously simulated. The results have shown that the performance of the APSIM-ORYZA model to simulate a continuous rice cropping system over time was acceptable.

The simple book-keeping approach used in ORYZA2000 to simulate soil nitrogen supply has proven robust and accurate when simulating leaf area index and rice yields growing under a range of nitrogen application rates, timings and split applications in lowland soils in the Philippines (Bouman and van Laar 2006). But the data used in that study were from the same environment where the two key nitrogen parameters (the indigenous nitrogen supply parameter and the fertiliser recovery coefficient) were derived. It has been suggested that the two nitrogen parameters are site-specific and need to be validated when applied to other environments (Bouman and van Laar 2006). In this study, the indigenous soil nitrogen supply parameter was calibrated based upon the field experiments at GARES. This step may ensure that the indigenous soil nitrogen supply (daily soil nitrogen supply available for uptake) was simulated correctly. Due to limited data, the fertiliser recovery coefficient remained uncalibrated. Bouman *et al*. (2001) suggested that the recovery of nitrogen fertiliser depends on the developmental stage of the crop described by a linearly increasing recovery fraction in the ORYZA2000 model ranging from 0.35 (from nitrogen applied at transplanting) to 0.75 (at panicle initiation). For this study, these values were applied unchanged for the Korean environment with satisfactory results for the seven levels of nitrogen fertiliser application. This suggests that this function adequately described the trend of fertiliser recovery for the Korean conditions, and that the indigenous nitrogen supplies may crucially affect the yield formation. However, those assumptions need to be validated using additional data.

The main shortcoming with the book-keeping approach was that it does not simulate the nitrogen transformation and translocation in the soil profile. Therefore, it was unable to be linked with other modules in APSIM that describe different processes associated with soil nitrogen, such as carbon dynamics and residue decomposition, which are important features of a long-term crop rotation system. Obviously a new routine to simulate nitrogen dynamics in paddy soil is needed for APSIM-ORYZA to simulate more management scenarios.

The meteorological data has shown that compared with the plants transplanted on 10 May, mid- and especially mid-to-late-maturing plants transplanted on 9 June experienced shorter daylengths during photoperiod-sensitive period. It has been suggested that the mid- and mid-to-late-maturing varieties are sensitive to the photoperiod (Lee *et al*. 2001; Kim *et al*. 1998*a*). Therefore, the short daylength accelerated the flowering processes of the mid- and mid-to-late-maturing plants when they were transplanted on 9 June. In this study, the photoperiod sensitivity parameters for the three Korean varieties could not be calibrated because of limited data, so the default values from the ORYZA200 model were used, based upon the IRRI variety, IR72 (Bouman *et al*. 2001). Therefore, it was not surprising that the simulated flowering dates of mid- and mid-to-late-maturing varieties transplanted in June were different from the measured flowering dates. Other studies have used linear regression methods to find the parameter values (Kim *et al*. 1998*b*; Lee *et al*. 2001), but these results may also be site-specific. Therefore, to accurately simulate flowering dates and yields of photoperiod sensitive varieties in Korea, it was necessary to calibrate the photoperiod sensitivity parameters.

In summary, although the calibration was limited to phonological parameters, the APSIM-ORYZA model accurately simulated yields in a long-term continuous rice-based production system. However, due to limited available data, the model's ability to simulate plant growth and nitrogen uptake at different growth stages could not be tested, limiting the interpretation of the results. Furthermore, the model was shown to adequately simulate rice yields under different nitrogen supply rates, the assumed values of the fertiliser recovery coefficients complicated the analysis of the nitrogen supply book-keeping routine for the Korean environment. It is acknowledged that this methodology cannot simulate nitrogen dynamics in the soil profile and carry-over effects of nitrogen in a long-term cropping system. It is recommended that a dynamic soil nitrogen model for paddy soils be developed to accommodate these requirements. In addition, the photoperiod sensitivity parameters of the Korean varieties need to be carefully calibrated to accurately predict the flowering dates and yields.

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