Improving resource use efficiency in rice-based cropping systems: Experimentation and modelling

Promotor:
Prof.dr.ir. H. van Keulen
Hoogleraar bij de Leerstoelgroep Plantaardige Productiesystemen, Wageningen Universiteit

Co-promotoren:
Dr.ir. H. Hengsdijk
Plant Research International, Wageningen Universiteit en Researchcentrum

Dr.ir. B.A.M. Bouman
International Rice Research Institute (IRRI), Philippines

Promotiecommissie:
Prof.dr.ir. Huub Spiertz
Wageningen Universiteit

Prof. Wang Guanghuo
Zhejiang University, Hangzhou, China

Dr. Michael Dingkuhn
Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France

Dr.ir. Hein ten Berge
Plant Research International, Wageningen Universiteit en Researchcentrum

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Qi Jing

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Abstract

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To cope with the projected increase in food demand and increased environmental concerns, rice-based cropping systems combining high resource use efficiencies and high yields will be increasingly important. By combining experimental research with crop growth simulation, this study aims at a better quantitative understanding of crop production and nitrogen dynamics in irrigated rice-wheat (RW) systems to improve N management as a basis for the design of RW systems that combine high yields with high N use efficiencies.

The various field experiments included different rice genotypes, environments, and N fertilizer and water management. Experimental data was used to evaluate the rice crop growth model ORYZA2000, which performed satisfactorily. The model was applied to explore options for different N management regimes combining high yields and high nitrogen use efficiency, and to identify the relative importance of environmental factors affecting yield and nitrogen use efficiency. Average rice yields of around 10-11,000 kg ha^{-1} were simulated with fertilizer N rates of around 200 kg ha^{-1}, with high nitrogen use efficiency in three equal splits at transplanting, panicle initiation and booting at Nanjing, China. Indigenous soil N supply affects yield and internal N use efficiency (INUE, kg grain per kg N uptake) more than weather at low N rate, but its effect is reduced at high N rate. Temperature contributes more than radiation to the variation in rice yield, N uptake and INUE.

The study resulted in better understanding of the relationship between yield and N dynamics in rice-based systems and in a RW model integrating existing crop and soil models and using results from own experiments. This model is a promising research tool to design and to develop rice-based cropping systems with high yields and high resource use efficiencies.

Key words: Nitrogen; Yield; Rice; Wheat; Environment; Simulation; Soil; Organic matter; Water; Denitrification

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Table of Contents

1 General introduction

1.1 Background

In next two decades world food demand is projected to increase with 60% due to the growing population (Cassman, 1999; FAO, 2003; Khush, 2005). Especially in Asia, population growth rates are high, while the demand is further increased through the shift in Asian diets from staples towards livestock and dairy products associated with the fast growing economies (Pingali, 2007). Rice is the major staple crop in Asia, from the cool sub-tropics to the warm humid tropics (Fig. 1.1). The total rice area in Asia is about 143 Mha, of which 73 Mha are irrigated, producing more than 70% of the global rice production (IRRI, 2002). In the tropics, two- or three-seasons of rice production per year are possible, depending on the availability of water. Only one rice crop per year can be grown in part of the sub-tropics, due to low temperatures in the winter period. Instead, winter crops, such as wheat and rapeseed, are grown in rotation with rice. Of these, rice-wheat (RW) cropping systems occupy 26 Mha in Asia, mainly in the Indo-Gangetic Plains (IGP) and the Yangtse River Basin of China (Fig. 1.2). Main characteristic of these RW-systems is the alternation of anaerobic (flooded) and aerobic soil conditions under rice and wheat, respectively (Timsina and Connor, 2001). China's rice area currently totals about 30 Mha, of which 90% is irrigated (Huang *et al.*, 2001), and 9-13 Mha is rotated with winter wheat, according to different estimates (Dawe *et al.*, 2004; Huke *et al.*, 1993; Ladha *et al.*, 2003; Timsina and Connor, 2001). The potential to expand the area for cereal production is limited because suitable land is scarce (Tong *et al.*, 2003). The current agricultural area is even expected to decrease in the future due to the increasing competition for land by urbanization and industrial development (Brockherhoff, 2000; Chen, 2007). Therefore, increased production per unit of area needs to be the main strategy to produce more food for a growing population.

Rice yields strongly vary over Asia, from less than 2 Mg ha^{-1} to more than 15 Mg ha^{-1} (Horie *et al.*, 1997; Romyen *et al.*, 1998; Whitbread *et al.*, 2003; Ying *et al.*, 1998a, b), depending on location and variety. A major cause of yield differences is the variation in environmental conditions, *i.e.* climate and soil (Horie *et al.*, 1997; Ying *et al.*, 1998a). In general terms, yield is the result of the interaction of Genotype (cultivar characteristics), Environment (climate and soil conditions) and Management (irrigation and fertilizer regime). The relative importance of each of these factors on yield in various environments is still poorly understood.

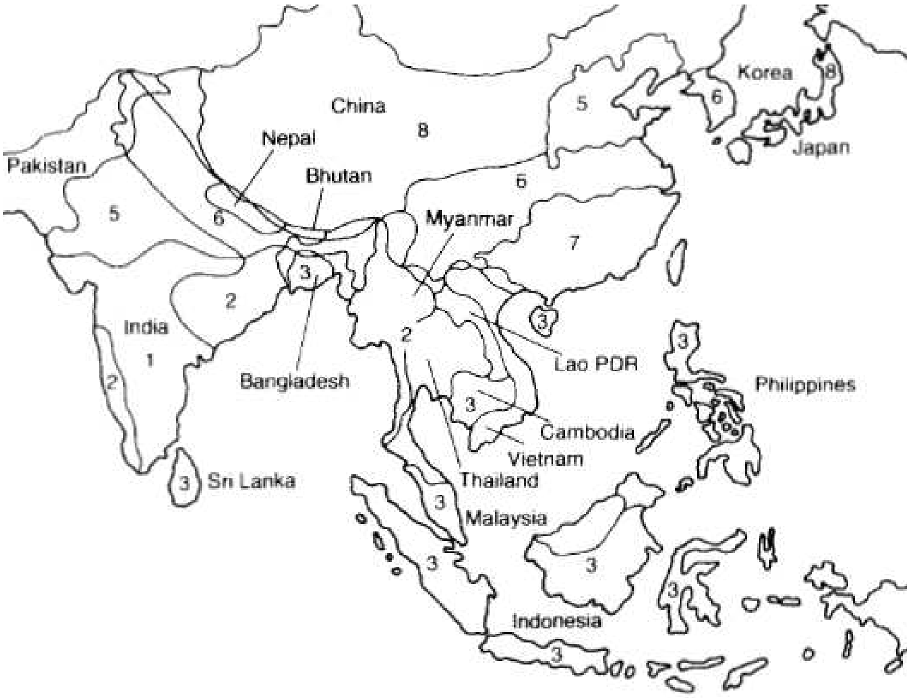


Figure 1.1 Agroecological zonation of Asia. Dominant agroecological zones: 1. warm semi-arid tropics; 2. warm sub-humid tropics; 3. warm humid tropics; 5. warm semi-arid sub-tropics with summer rainfall; 6. warm sub-humid subtropics with summer rainfall; 7. warm/cool humid sub-tropics with summer rainfall; 8. cool sub-tropics with summer rainfall. (Source: IRRI, 2002).

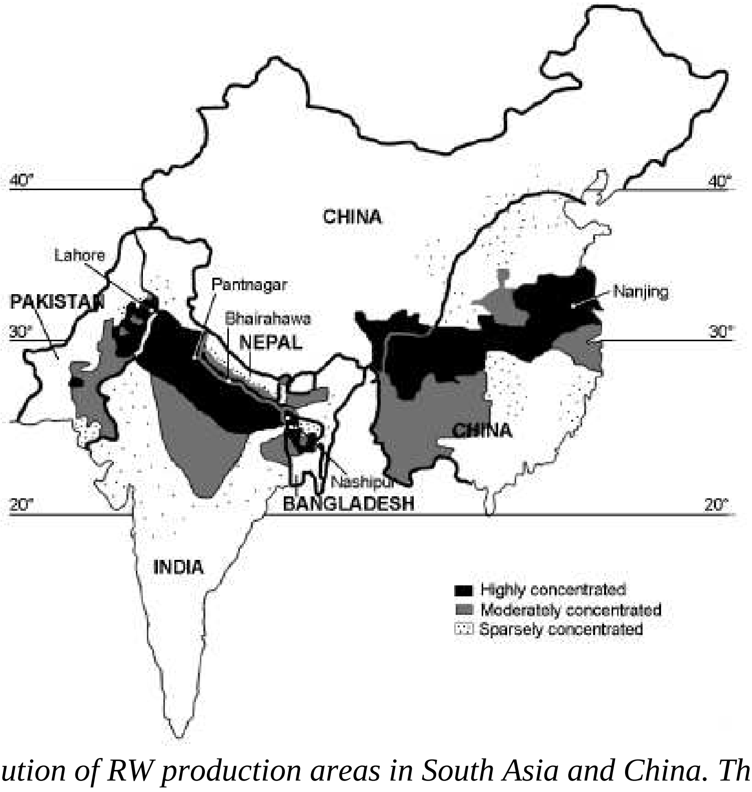


Figure 1.2 Distribution of RW production areas in South Asia and China. The curve passing from northeast to southwest China represents the limits for growing RW sequences in China (Source: Timsina and Connor, 2001).

1.2 Challenges in rice-based cropping systems

Especially the use of mineral fertilizers in China has contributed to the spectacular yield increase in RW systems between the 1960's and 1990's. Recent studies show that yields of both crops stabilize and do not increase as rapidly as in the past (Fig. 1.3). As a result, agronomic efficiency of nitrogen, *i.e.* the incremental increase in grain yield that results from N application, deceased in rice from 160 kg kg^{-1} in 1961 to 10 kg kg^{-1} in 1996, and in wheat from 44 to 6 kg kg^{-1} (Tong *et al.*, 2003). Among the provinces with intensive RW cropping systems in China, average fertilizer N input is highest in Jiangsu with rates of about 500 kg N per ha per year (Zhu *et al.*, 2000). Associated fertilizer N recovery is 30~35% in both crops (Li *et al.*, 2000; Peng *et al.*, 2002; Zhu and Chen, 2002). On the one hand, excessive N fertilizer rates have increased emissions of greenhouse gases and pollution of water resources (Richter and Roelcke, 2000; Xing and Zhu, 2000; Zhang *et al.*, 1996; Zhu *et al.*, 2000; Zhu *et al.*, 2003; Zhu and Chen, 2002), while on the other hand increased fertilizer inputs have increased production costs resulting in lower net returns for farmers (Wang *et al.*, 2001). Future rice-based crop production should aim at high yields combined with high nitrogen use efficiency, thus increasing farmers' profitability and limiting negative environmental externalities.

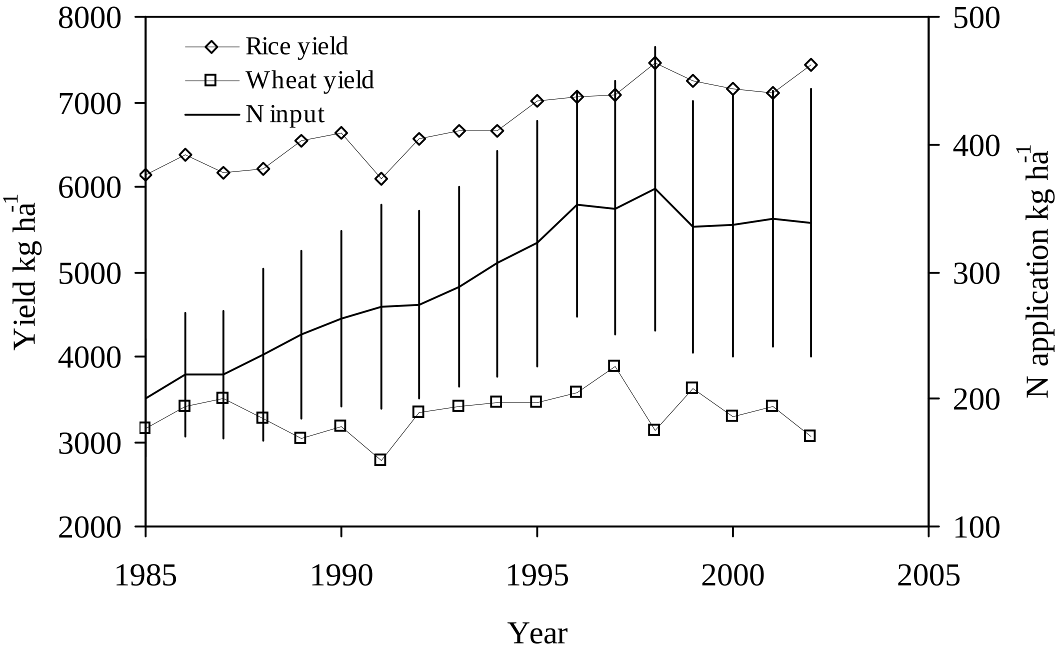


Figure 1.3 Trends in N input and yields of rice and wheat in RW systems in China. Yields and N inputs are the means of Jiangsu, Anhui, Hubei and Sichuan Provinces. Bars are the deviations of N inputs among provinces (Source: China Statistical Yearbook, 2004).

Irrigated rice-based cropping systems are among the major water users in Asia and account for around half of all diverted freshwater in Asia. Rice is usually irrigated with 2 to 3 times more water than other irrigated cereals (Tuong *et al*., 2005). The increasing scarcity of water and competing claims on water by other sectors (CA, 2007; FAO, 2003) require that agriculture uses water resources more efficiently than in the past. Recent research has focused on water-saving technologies, especially in rice cultivation. A range of new irrigation and cultivation methods have been developed, which basically consist of growing rice under more aerobic conditions, *i.e.* no continuous flooding during the growing season. Avoidance of a continuous water layer reduces water losses due to percolation, drainage and evaporation (Bouman *et al*., 2007). The alternation of aerobic and anaerobic field conditions in rice systems affects the sustainability of rice production, environmental impact, and N dynamics.

1.3 Simulation of rice-based cropping systems

Cropping systems consist of numerous complex and interacting biological processes, which can be influenced by human management. Quantification of these complex processes helps to increase understanding of crop growth and facilitates the design of new management strategies aimed at combining high yields and high resource use efficiencies. Modelling is an important tool to explicitly describe the relationships between the various components of complex systems (Jones *et al*., 2003; Keating *et al*., 2003; Van Ittersum *et al*., 2003). It increases insight into relevant processes, allows study of the effects of crop management, and exploration of possible consequences of management modifications. Once a model has been parameterized and validated, it can be used in support of analysis and interpretation of field experiments, for extrapolation of experimental results over a wider range of management practices and weather conditions, and to explore and derive, for example, efficient N management strategies (Bouman *et al*., 1996).

Since the 1980's, many crop models have been developed (Hoogenboom *et al*., 2004; Jones *et al*., 2003; Keating *et al*., 2003; Van Ittersum *et al*., 2003). The crop growth models CERES-Rice and CERES-Wheat (CERES, Crop Estimation through Resource and Environment Synthesis) have been applied for studying RW systems in northern Bangladesh and northwest India (Sarkar and Kar, 2006; Timsina *et al*., 1998). Existing models have problems simulating RW systems as various soil processes perform quite differently under anaerobic and aerobic conditions, a main feature of these systems (Probert, 2002; Shibu *et al*., 2006; Timsina and Connor, 2001; Timsina and Humphreys, 2006). A comprehensive modelling framework that is able to simulate crop growth under both contrasting soil conditions does not yet exist.

1.4 Objectives

This study aims at better understanding of crop growth and nitrogen dynamics in irrigated RW systems as a basis for improved N management in these systems as a component in the design of RW systems that combine high yields of the desired quality with high N use efficiency. I combine experimental and modelling approaches to improve insight in the underlying processes.

Specific objectives of my study comprise:

- Quantification of the contribution of genotype and environment to yield and grain quality, and identification of the relative importance of environmental factors affecting yield and N use efficiency of rice.
- Assessment of the relative effects of indigenous soil N supply and N-fertilizer regimes on yield of irrigated rice, as a basis for the design of improved N management strategies for high-yielding and N use efficient irrigated rice-wheat systems in China.
- Analysis of the N response and N use efficiency in RW systems through a dedicated field experiment.
- Development of a rice-wheat rotation model (RIWER) for quantification of N dynamics and exploration of management options aimed at high resources use efficiency in RW systems.

1.5 Outline of the thesis

The background and justification of this study are described in this Chapter. Based on results of a multi-location rice experiment across Asia, Chapter 2 quantifies the effects of genotype, environment and their interactions on grain yield and quality. Data from these experiments in combination with the rice growth model ORYZA2000 are used in Chapter 3 to analyse the contribution of environmental factors to yield and N use efficiency. Chapter 4 examines N management strategies to increase N use efficiency in rice using a modelling approach. Chapter 5 describes the results of a two-year RW experiment aimed at quantifying N response and N use efficiency in RW systems. A RW-simulation modelling framework has been developed, based on existing models and aiming at comprehensive analysis of RW systems. The model RIWER (RIce WhEat Rotation) is described in Chapter 6. Finally, general conclusions are presented and prospects for model application in resource use analysis and management are discussed in Chapter 7.

2 The performance of five rice genotypes in tropical and subtropical environments: Grain yield and quality

Qi Jing[1,2,3], Huib Hengsdijk[2], Herman van Keulen[2,3], Weixing Cao[1], Tingbo Dai[1]

[1] Hi-Tech Key Lab of Information Agriculture of Jiangsu Province, Nanjing Agricultural University, Nanjing 210095, China
[2] Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA Wageningen, the Netherlands
[3] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, the Netherlands

Abstract

The consequence of the still rapidly growing population of Asia is an increasing demand for rice with well-defined grain quality characteristics. Yield and quality of rice depend on the interaction between genotypic characteristics and environmental conditions. This study describes the results of field experiments in eight agro-ecological zones of the tropics and subtropics across Asia during 2001 and 2002. The aim of the standardized experiments was to study the performance of five rice genotypes in terms of yield, harvest index (HI) and quality (protein and amylose content) in different environmental conditions. The genotypes included Japonica× indica crossbred Takanari, indica IR72, japonicas Nipponbare and Takenari, and the indica×javanica crossbred IR65564-44-2-2.

There were significant differences in grain yield, HI, protein content, and amylose content among genotypes. Averaged over locations and years, yields and HIs of Takanari were highest, while amylose content of IR72 was highest. Environmental differences explained 80% of the observed variation in grain yields, and 66% of the variation in HIs. Low yields at tropical locations were associated with low radiation interception, resulting from fast phenological development during the vegetative phase, and low HI resulting from poor grain formation during the reproductive phase. The variation among genotypes in yield and HI could be well described by second order polynomial equations based on average temperature during the ripening period (ATR). Amylose content of rice grains differed among genotypes, which explained 72% of the total variation, compared to 24% by environmental conditions. Grain amylose content was linearly and inversely correlated to ATR. Protein content was not significantly different among locations mainly because of the similar N management across experiments.

Results may support selection of genotypes for targeted yield and quality characteristics under well-defined environmental conditions, and provides information for adapting crop management (*e.g.* sowing date).

In addition, the multi-location data set can be used to improve dynamic rice simulation models with respect to simulation of grain quality and better characterization of different rice genotypes.

Key words: yield formation; harvest index; protein content; amylose content.

2.1 Introduction

Asia's irrigated rice area of 73 Mha produces more than 70% of the global rice production (Maclean *et al.*, 2002). About two-thirds of this area is located in the tropics and the remainder in the subtropics (Hossain and Laborte, 1993). To cope with the projected population growth and the associated increase in food demand, average irrigated rice yields in Asia must increase with 60% from 4.9 t ha^{-1} to 8 t ha^{-1} in 2025 (IRRI, 1995). Yields in tropical areas are often below 5 t ha^{-1} (Dobermann *et al.*, 2003a; Romyen *et al.*, 1998; Whitbread *et al.*, 2003), while those in subtropical areas often exceed 6 t ha^{-1} (Dobermann *et al.*, 2003a; Horie *et al.*, 2003; Jing *et al.*, 2005). Past research has compared the productivity of rice in subtropical and tropical areas to identify growth factors contributing to this difference. For example, Ying *et al.* (1998a) found in two years that the same high-yielding genotypes yielded 33 and 62% more under subtropical than under tropical conditions. In these experiments, under optimum management and ample supply of water and nutrients, temperature and radiation were the main yield-determining factors (Van Ittersum and Rabbinge, 1997). However, effects of these climatic factors were not further analyzed in these experiments. Horie *et al.* (1997) reported that irrigated rice yields were affected by genotypic characteristics, location and their interaction (G×E). However, they did not quantify the contribution of the individual factors to the yield variance.

Remarkably, very few attempts have been made to analyze the performance of irrigated rice across subtropical and tropical areas in Asia. Where available, such reports are descriptive and do not explain yield differences (Ying *et al.*, 1998a). Sound comparison among sites is only possible when experiments are carried out and data collected according to standard protocols. This is difficult to realize, which may explain the scarcity of systematically collected empirical information on the interaction between rice genotypes and environments across Asia. Better understanding of genotype-environment interactions facilitates design of new genotypes, identification of test conditions, and genotype selection for specific well-defined conditions (Jackson *et al.*, 1996; Yan and Hunt, 1998).

Yield is a function of biomass production and the proportion of that biomass invested in the grains (harvest index, HI) (Cock and Yoshida, 1972; Murata and Matsushima, 1975). Future yield increase must result from improvements in one or both components (Farrell *et al.*, 1998). Intercepted photosynthetically active radiation (IPAR) and crop-specific radiation-use efficiency (RUE, biomass produced per unit of IPAR) determine biomass production. Assimilates for grain filling originate from photosynthesis after flowering and from reserves stored in culms and leaves during the vegetative period. Longer crop growth durations, leading to higher radiation interception, result in higher yields if associated with favorable RUE and HI. High temperatures during vegetative growth stages accelerate crop development, shortening crop growth duration, resulting in lower grain yields. The photothermal quotient (PTQ, the ratio of average radiation intensity to average temperature during the grain filling period) has been proposed as a single indicator to capture the combined effect of the yield-determining factors radiation and temperature on yields (Nix, 1976).

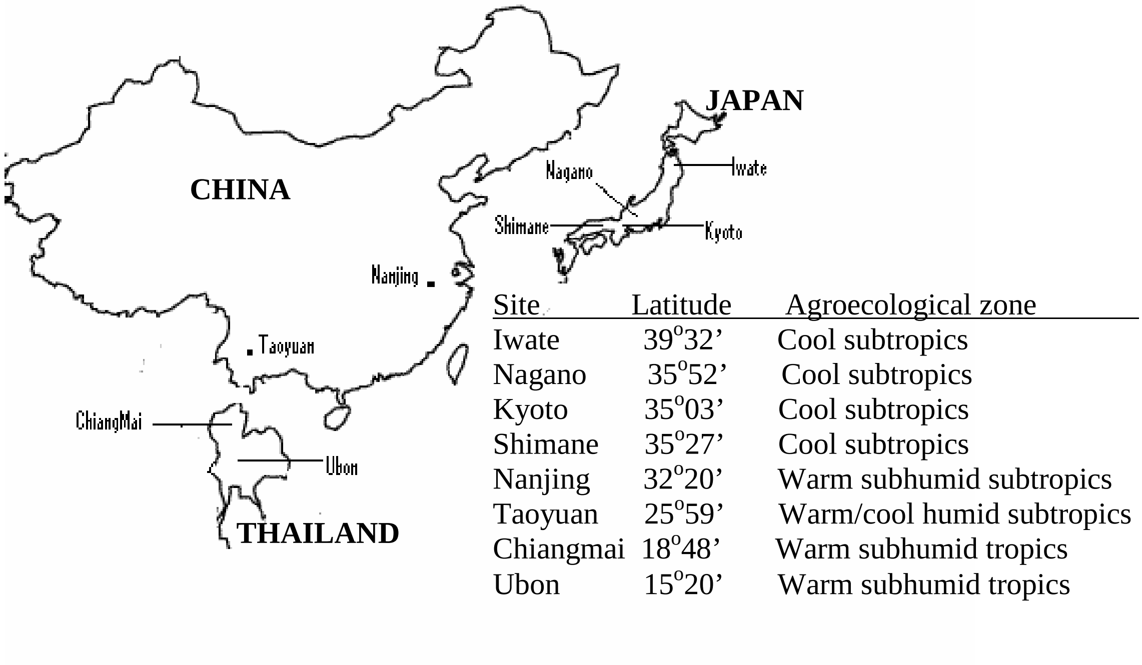
As basic food security in Asia improves, demand for rice with superior quality properties increases. Grain quality will become even more important in the future, when the economic situation of the very poor—many of whom depend on rice as their staple food—improves and they demand higher quality rice (Juliano and Villareal, 1993). The nutritional value of rice is related to its protein content, while its amylose content is an important indicator of cooking and consumption quality (Juliano, 1985; Lii *et al.*, 1996). Low amylose content increases water absorption, volume expansion, and stickiness of cooked rice (Delwiche *et al.*, 1996), while high amylose content is associated with hard grains after cooking (Juliano, 1998). Preferences for soft and hard rice grains vary widely across Asia. Quality characteristics of rice are formed during grain filling, and are determined by environmental and genotypic factors and their interactions. However, these interactions are poorly understood, which hampers breeding of rice varieties with targeted quality characteristics. Systematic data on quality characteristics of different rice varieties grown under tropical and sub-tropical conditions are scarce.

The objective of this study is to compare and evaluate grain yield and grain quality (protein content and amylose content) among five rice genotypes (G) in two tropical and six subtropical environments (E) in Asia, and to examine their variation on the basis of environment × genotype interactions (G×E). To realize this objective, multi-location experiments with these genotypes have been carried out, using a standard protocol, which are described in the section materials and methods. In the results section, variations in grain yield and quality among genotypes and locations and their interactions are analyzed. To better understand and explain the results, RUEs, PTQs and the relationships between on the one hand average temperature during ripening (ATR) and on the other hand yield, HI and grain amylose content are quantified. Finally, results are discussed with respect to their contribution to the rice research agenda.

2.2 Materials and methods

2.2.1 Experimental locations

The two-year multi-varietal field experiments were carried out in South and East Asia in the framework of the Asian Rice Network (ARICENET) (Horie *et al.*, 2003), according to a standard protocol for experimental design, crop management, observations, measurements and processing of collected data. In 2001, there were seven experimental sites of which five in subtropical regions, *i.e.* Iwate, Nagano, Kyoto and Shimane in Japan, and Nanjing in China, and two in tropical regions, *i.e.* Chiangmai and Ubon in Thailand (Fig. 2.1). In 2002, the subtropical location Taoyuan in China was added.



Site	Latitude	Agroecological zone
Iwate	39°32’	Cool subtropics
Nagano	35°52’	Cool subtropics
Kyoto	35°03’	Cool subtropics
Shimane	35°27’	Cool subtropics
Nanjing	32°20’	Warm subhumid subtropics
Taoyuan	25°59’	Warm/cool humid subtropics
Chiangmai	18°48’	Warm subhumid tropics
Ubon	15°20’	Warm subhumid tropics

Figure 2.1 Location of the experimental sites and the agroecological zonation based on Maclean et al. (2002).

2.2.2 Experimental design and crop management

At each experimental site, five genotypes were tested, including indica, japonica, indica×japonica, and indica×javanica types (Table 2.1). All experiments had a randomized block design with 3 replicates and a plot size of 20 m^2. At transplanting, 40 kg N ha^{-1} was applied, and 20 kg N ha^{-1} was top-dressed every 20 days until 10 days after heading, so that N fertilizer supply (in kg ha^{-1} d^{-1}) varied from 0.94 at Nagano and Shimane to 1.05 at Chiangmai. In addition, 120 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1} were applied as a basal dressing. Rice seedlings with 4 to 5 leaves, depending on genotype, were transplanted at 2 plants $hill^{-1}$, spaced at 30 cm between the rows and 15 cm within. During the experiments, experimental fields were continuously flooded, and weeds, pests and diseases were adequately controlled by biocides.

Table 2.1 Genotypes, their acronyms, plant type and characteristics.

Genotype	Acronym	Plant type	Characteristic
Takanari	TA	indica×japonica crossbred	High-yielding
IR72	IR	indica	IRRI standard
IR65564-44-2-2	NP	indica×javanica crossbred	New plant type of IRRI
Nipponbare	NI	japonica	Japanese standard
Takenari	TE	japonica	Japan old genotype

2.2.3 Observations and measurements

The vegetative period is defined in this study as time from emergence to panicle initiation, the reproductive period from panicle initiation to flowering, and the ripening period from flowering to maturity. Panicle initiation was identified as the moment that the panicle was visible as a white feathery cone of 1.0-1.5 mm in the main culm, flowering as the moment the stamen were visible, while maturity was recorded when less than 10-15% of the grains was still green-colored. At transplanting, 20 plants were sampled for each genotype; at 20 days after transplanting, panicle initiation, two weeks before flowering, flowering, two weeks after flowering, and at maturity, eight hills per genotype were harvested for green leaf area measurement, and leaf area index (LAI) was calculated. At maturity, plants were partitioned into leaves, stems combined with sheathes, and panicles, and were dried till constant weight in an oven at 80 ºC. Spikelet numbers per panicle were measured, the spikelet fertility was determined from the number of filled grains per panicle, filled grains were selected in a NaCl solution with a specific gravity of 1.03. Grain yield were measured on a plot of 2 m^2, yield was expressed at a moisture content of 14%. Harvest index (HI) was defined as grain yield divided by total aboveground dry weight.

Protein and amylose contents of rice grains were determined in Iwate, Kyoto and Nanjing in 2001, and in Shimane, Nanjing, Taoyuan and Chiangmai in 2002.

Grain samples were threshed milled and ground in preparation for protein and amylose analysis. N content was determined by micro-Kjeldahl digestion, distillation, and titration, and converted to protein content by multiplication by 5.95 (Juliano and Villareal, 1993). Amylose content was determined according to the modified assay described by Juliano *et al*. (1981) and Juliano and Villareal (1993). Daily weather data recorded at weather stations at each experimental location, included radiation (RD) and maximum (T_{max}) and minimum (T_{min}) temperature.

2.2.4 Data analysis

GenStat for Windows, 8th Edition (http://www.vsn-intl.com/genstat/) was used in data analysis, *i.e.* establishing effects of genotype, location and year, and their interactions on yield, harvest index, protein content and amylose content. The method of residual maximum likelihood (REML) was used, which provides efficient estimates of treatment effects in unbalanced designs and allows analysis of incomplete data sets (data of Taoyuan for 2001 were missing) (Welham and Thompson, 1997). Statistical differences were determined using Wald statistics. Average values of analyzed variables for the two years are given when the year × genotype interaction was not significant.

GenStat was also used to determine regressions of daily average temperature during ripening (ATR) on yield, HI, and amylose content.

Intercepted photosynthetically active radiation (IPAR) was calculated from radiation:

$$IPAR = 0.5 \times RD \times (1 - e^{-k \times L}) \qquad \text{(eqn 2.1)}$$

where k is the light extinction coefficient of rice, which is set to 0.4-0.6 depending on the crop development stage as used in the rice crop growth model ORYZA2000 (Bouman *et al*., 2001); L is daily leaf area index of the canopy, calculated by linear interpolation from measured LAI at various growth stages.

PTQ is defined by Nix (1976) as the ratio of mean daily total incident solar radiation for an interval to the mean temperature minus a base temperature. It is a gross measure of light energy available for photosynthesis per unit of developmental unit, a high PTQ indicates that more biomass is produced per developmental unit. Considering the differences in crop phenology at the different locations, PTQ was calculated over a period of 30 days prior to anthesis (Islam and Morison, 1992), using intercepted radiation (Fischer, 1985):

$$PTQ = \frac{IRD}{0.5 \times (T_{\min} + T_{\max}) - T_b} \qquad \text{(eqn 2.2)}$$

where *IRD* is intercepted radiation, calculated from measured radiation using equation (1), T_{min} and T_{max} are daily minimum and maximum temperature, respectively, while T_b is the base temperature, for rice set to 8 °C.

2.3 Results

2.3.1 Weather and growth duration

Daily average radiation and temperature during the three phenological stages at the eight locations are shown in Table 2.2. The variation in radiation among growth periods was in general smaller in both tropical locations than in the sub-tropical areas. On average, radiation was higher in the subtropical locations during the vegetative and reproductive growth periods, but was highest in both tropical locations, Chiangmai and Ubon, during the ripening period.

Table 2.2 Daily average incoming radiation and average temperature during the vegetative (V), reproductive (Re), and ripening (Ri) stages of rice at eight locations in Asia (average of 2001 and 2002).

Location	Daily average radiation ± *sd* (MJ m^{-2} d^{-1})						Daily average temperature ± *sd* (^{o}C)					
	V	*sd*	Re	*sd*	Ri	*sd*	V	*sd*	Re	*sd*	Ri	*sd*
Iwate	15.7	0.04	13.3	0.27	10.6	0.49	18.9	0.22	23.1	0.05	16.6	0.91
Nagano	19.1	0.18	20.2	0.89	13.9	0.50	20.2	0.24	24.2	0.26	22.1	0.69
Kyoto	15.5	0.13	15.1	0.24	12.5	0.24	22.9	0.26	27.7	1.05	25.0	0.57
Shimane	16.0	0.11	18.7	0.51	13.0	0.70	21.1	0.28	27.8	0.33	23.6	0.87
Nanjing	15.4	0.02	14.4	0.31	14.1	0.22	27.2	0.06	27.7	0.66	24.8	0.78
Taoyuan	18.6	0.11	16.8	1.49	15.3	1.62	25.2	0.11	25.6	0.63	24.2	0.35
Chiangmai	14.9	0.55	16.0	0.24	15.9	0.21	28.1	0.16	27.7	0.37	26.2	1.11
Ubon	17.0	0.18	16.1	0.74	15.8	0.71	28.5	0.06	28.2	0.15	27.7	0.22

Vegetative is from emergence to panicle initiation, reproductive from panicle initiation to flowering, ripening from flowering to maturity.
sd is standard deviation for the five genotypes.

Daily average temperature in subtropical locations was highest during the reproductive growth period, while in tropical locations it was lower during the ripening period than during the vegetative period. Average daily temperature during ripening was lowest in Iwate (16.6 °C), *i.e.* about ten degrees lower than in Chiangmai and Ubon. The large standard deviation of daily temperature during ripening at Chiangmai is associated with large differences in growth duration of genotypes at this location.

Average lengths of the phenological stages, *i.e.* vegetative, reproductive, and ripening, at each location are shown in Fig. 2.2. At the subtropical locations, the vegetative and ripening periods were longer, while the reproductive periods were shorter than at the tropical locations. At the subtropical locations, the vegetative periods were substantially longer than the reproductive and ripening periods, while in both tropical locations, the vegetative periods were much shorter, at Ubon even shorter than the reproductive period. Ripening periods at Chiangmai and Ubon were on average shorter than those at the subtropical sites.

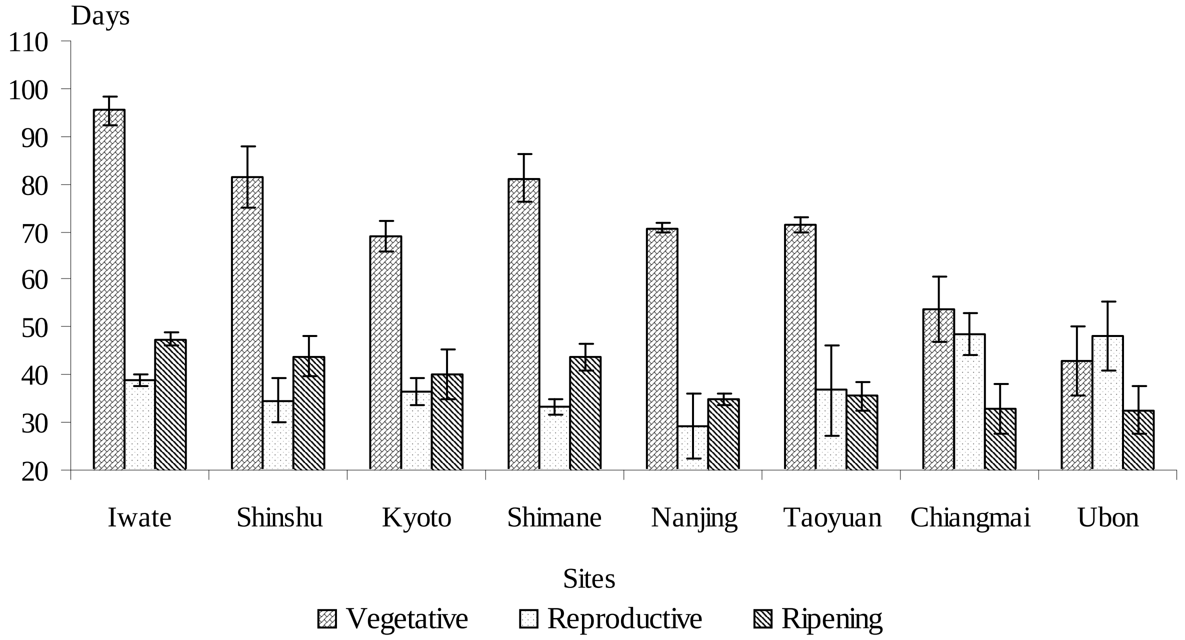


Figure 2.2 Average length of the three phenological stages of five rice genotypes at eight experimental sites in Asia. Vegetative phase is from emergence to panicle initiation, reproductive from panicle initiation to flowering, ripening from flowering to maturity. Bars in each column represent the standard deviation among five genotypes.

2.3.2 Yield

Yield variation across locations and genotypes

Average yields across experimental locations were significantly different among the five genotypes (Table 2.3). In general, yields of the indica×japonica crossbred (TA) and the indica genotype (IR) were higher than those of the japonica genotypes (NI and TE) and the indica×javanica crossbred (NP). TA attained the highest average yields and the new genotype developed at IRRI (NP) the lowest.

Table 2.3 Average grain yield, harvest index (HI), protein content and amylose content of five rice genotypes across different locations in South and East Asia in two years (2001 and 2002).

Genotype	Yield (kg ha^{-1})		Harvest index(-)		Protein content (%)		Amylose content (%)	
TA[a]	7613	a[b]	0.48	A	8.0	a	8.5	d
IR	6619	b	0.42	B	7.1	ab	19.9	a
NP	5430	c	0.35	C	7.0	b	10.3	bc
NI	5880	c	0.41	B	7.4	ab	9.7	c
TE	5932	c	0.39	Bc	7.5	ab	10.8	b
Source of variation and its contribution[c]								
Location (L)	0.807 (**)		0.655 (**)		(NS)		0.238 (**)	
Genotype (G)	0.092 (**)		0.215 (**)		0.266 (*)		0.721 (**)	
L × G	0.101 (**)		(NS)		(NS)		0.041 (**)	
Year	(*)		(*)		(*)		(**)	
Year × G	(NS)		(NS)		(NS)		(NS)	

[a] See Table 2.1 for explanation of acronyms.

[b] Within a column, values followed by different letters (a-d) are significantly different at the 0.05 probability level.

[c] Calculated as sum of square (SS) of environment divided by total SS (SST).

*, ** Significant at the 0.05 and 0.01 probability levels.

Grain yields were consistently low at Iwate, Chiangmai and, especially, Ubon (Table 2.4). Yields for all five genotypes were highest in Taoyuan, while Kyoto scored second for TA, IR, NP, and TE in both years. Location explained 80.7% of the yield variation (sum of squares), genotype 9.2%, and the remainder was due to their interaction (Table 2.3).

Table 2.4 Grain yields (kg ha^{-1}) of five genotypes at different locations in Asia (average of 2001 and 2002).

Location	Genotype					
	TA[a]	IR	NP	NI	TE	Average
Iwate	6593 c[b]	3902 de	2957 e	5360 c	5308 c	4824
Nagano	9093 b	6164 c	5850 bcd	7679 ab	7558 b	7269
Kyoto	10009 ab	9145 a	7159 ab	6769 bc	6758 bc	7968
Shimane	9097 b	8580 ab	6868 bc	7257 b	7134 b	7787
Nanjing	8527 b	6906 bc	5310 cd	6500 bc	6878 bc	6824
Taoyuan	10928 a	10618 a	9301 a	9749 a	10432 a	9920
Chiangmai	4564 d	5456 cd	5029 d	1939 d	1978 d	3793
Ubon	1646 e	2184 e	966 f	1448 d	1499 d	1505

[a] See Table 1 for explanation of acronyms;

[b] Within a column, values followed by different letters (a-f) are significantly different at the 0.05 probability level..

Response to temperature during ripening

The relationship between average daily temperature during the ripening phase (ATR) and yield (Y) can be described by a polynomial (Fig. 2.3):

$$Y = Y_{\max} + s(x - ATR_{\max})^2 \qquad \text{(eqn 2.3)}$$

where Y_{max} is maximum yield under given crop management, ATR_{max} optimum ATR for obtaining Y_{max} and *s* a shape parameter describing the steepness of the curves.

The parameter *s* (Table 2.5) is constant for all genotypes (s = -172.5), indicating constant relative decline in yields per degree temperature difference from optimum ATR. ATR_{max} of the indica and indica-japonica crossbred genotypes, TA and IR, is significantly higher than that of the japonica genotypes, indicating the better adaptation of the latter to lower temperatures during ripening. At optimum ATR, Y_{max} of NP under the management applied, is lower than those of the other genotypes, that do not show significant differences, in contrast to the yields obtained in the experiments (Table 2.4). This implies that for these genotypes ATR was suboptimal in the experiments.

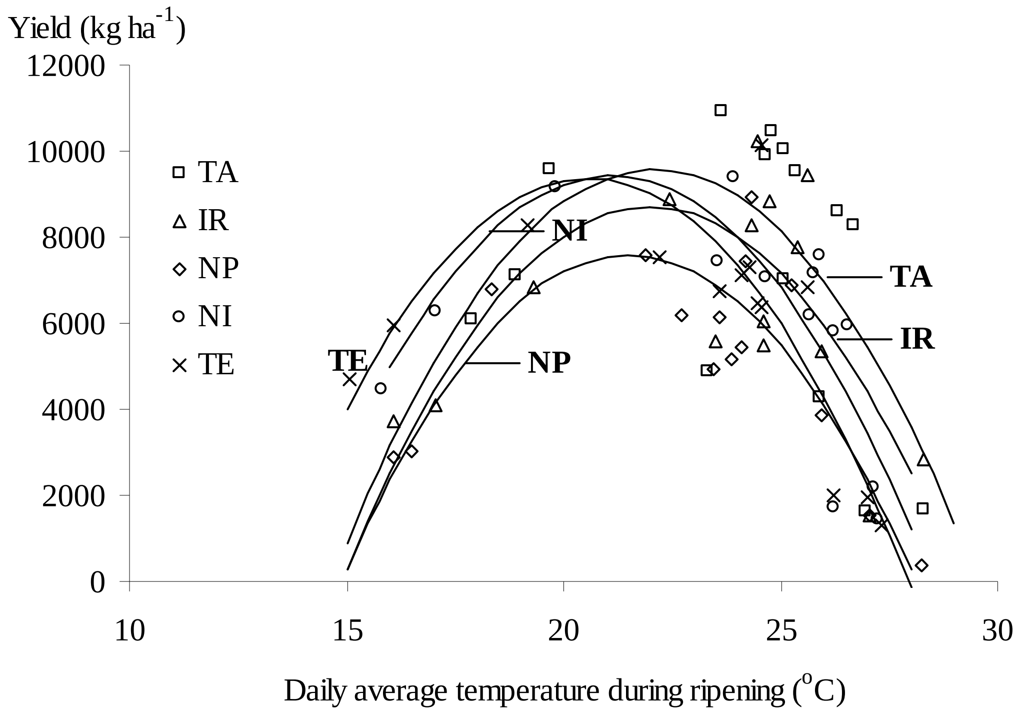


Figure 2.3 Relation between yield and average daily temperature during the ripening stage for the different genotypes at different sites in Asia during 2001 and 2002. See Table 2.1 for explanation of acronyms of genotypes.

Table 2.5 Parameters of fitted curves of second order polynomials for yield (Y_{max}) and harvest index (HI) on daily average temperature during the ripening phase.

Genotype	Yield						HI					
	$Y_{\max}$	se^b	$ATR_{\max}$	*se*	s	*se*	$HI_{\max}$	*se*	$ATR_{\max}$	*se*	s	*se*
TA[a]	9579	*585*	22.1	*0.45*	-172.5	*18.7*	0.56	*0.03*	22.3	*0.53*	-0.006	*0.0008*
IR	8711	*566*	22.0	*0.39*	id.	*id.*	0.50	*0.02*	22.2	*0.46*	id.	*Id.*
NP	7579	*556*	21.5	*0.38*	id.	*id.*	0.43	*0.02*	21.7	*0.45*	id.	*Id.*
NI	9441	*682*	21.1	*0.38*	id.	*id.*	0.53	*0.03*	21.8	*0.45*	id.	*Id.*
TE	9368	*657*	20.6	*0.38*	id.	*id.*	0.50	*0.03*	21.3	*0.44*	id.	*Id.*

[a] See Table 2.1 for explanation of acronyms

[b] *se* is standard error.

PTQ analysis

Yield for all genotypes was positively and significantly correlated with the PTQ 30 days prior to anthesis (Fig. 2.4), although the relation was different for the japonica genotypes, TE and NI, on one hand and the indica IR and the crossbreds TA and NP on the other hand. In general, the japonica genotypes show higher yields at lower PTQs and lower yields at higher PTQs than the indica and the crossbreds, suggesting lower yield increase per unit of developmental time for the japonica genotypes.

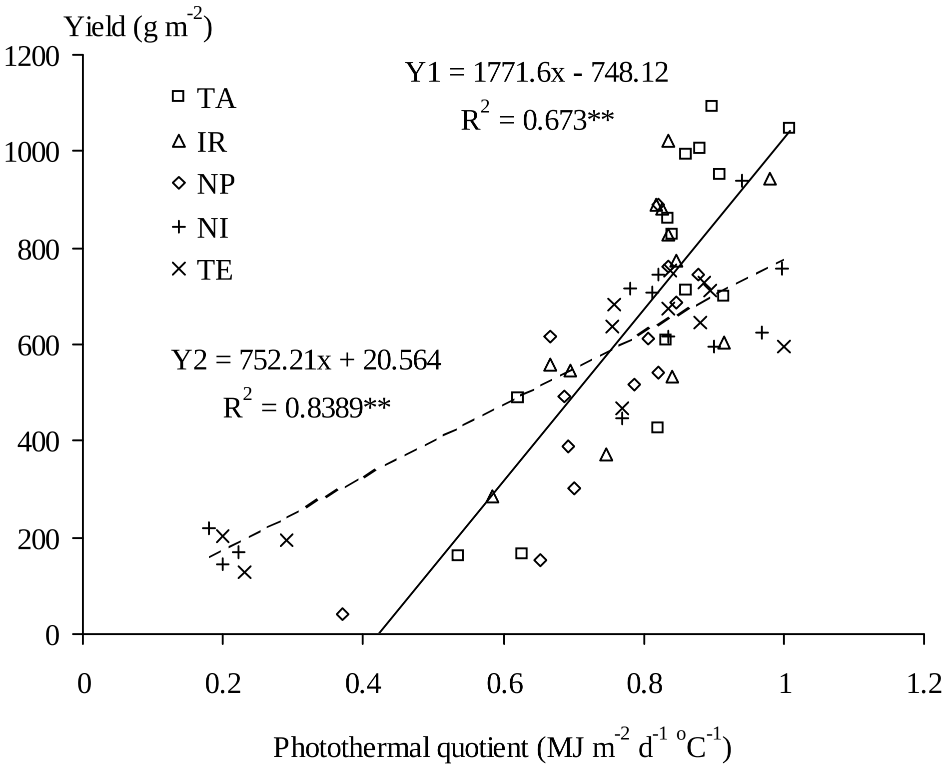


Figure 2.4 *Relation between grain yield and photothermal quotient 30 days prior to anthesis in two years for different genotypes at different locations in Asia. Solid line (Y1) is for indica IR and crossbreds TA and NP; dotted line (Y2) is for japonica cultivars. ** Correlation coefficients significant at 0.01 level. See Table 2.1 for explanation of acronyms.*

2.3.3 Radiation use efficiency (RUE)

Radiation use efficiency varied among genotypes between 1.87 and 2.11 g MJ^{-1}, as illustrated in Fig. 2.5 for specific locations. RUE also varied among locations for the same genotype. Maximum RUE was around 2.8 g MJ^{-1} at Taoyuan, followed by 2.3 g MJ^{-1} at Chiangmai, while at Nagano, Kyoto, Shimane and Nanjing RUEs ranged from 1.8 to 2.0 g MJ^{-1}. Average RUEs at Iwate and Ubon were 1.6 and 1.5 g MJ^{-1}, respectively.

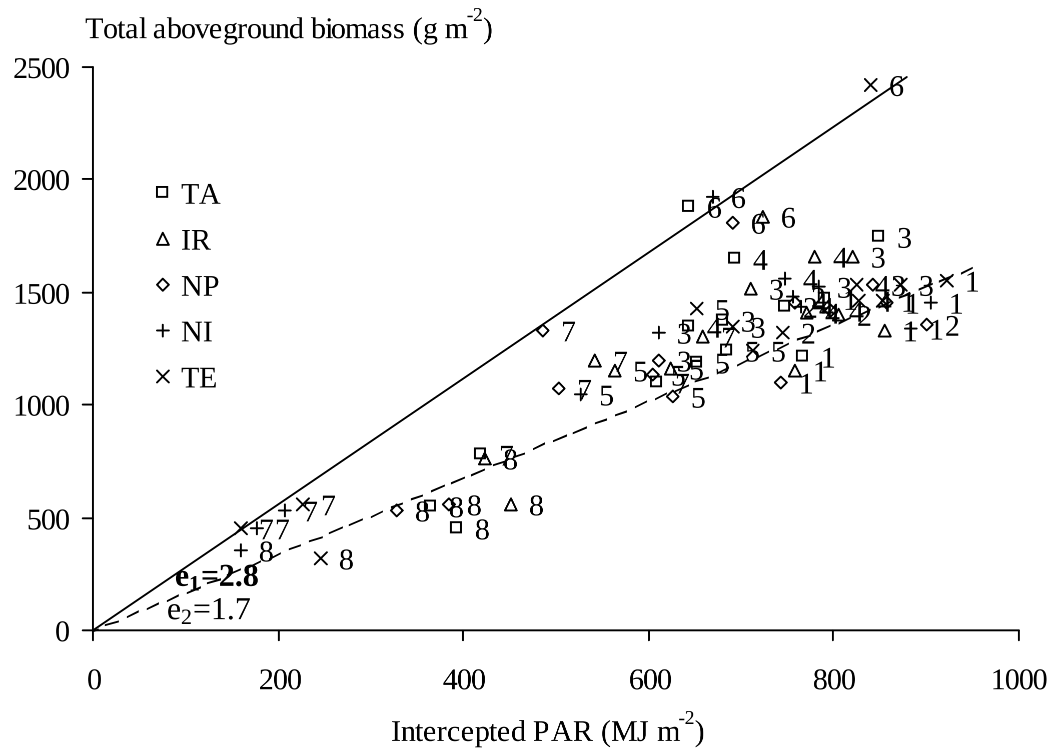


Figure 2.5 *Relation between total aboveground biomass (dry matter) and total intercepted photosynthetically active radiation (PAR). Numbers near the symbols refer to the locations: 1 Iwate; 2 Shinshu; 3 Kyoto; 4 Shimane; 5 Nanjing; 6 Taoyuan; 7 Chiangmai; 8 Ubon. See Table 2.1 for explanation of acronyms.* e_1 *is the slope of the solid line,* e_2 *is the slope of the dotted line.*

2.3.4 Harvest index (HI)

Variation across locations and genotypes

The high yield of TA was associated with a HI significantly higher than those of the other genotypes (Table 2.3), whereas NP had the lowest HI. Overall, high yields in the experiments were associated with high HIs.

Average HI for a specific genotype varied significantly among experimental locations (Table 2.6), from the lowest in Ubon, via Iwate, Chiangmai, Taoyuan, Shimane, Kyoto and Shinshu, to the highest in Nanjing, illustrating the effect of environmental conditions on HI. HI was thus lowest for the most northern and most southern location, *i.e.* Iwate (39° N) and Ubon (15° N). Differences in environmental conditions among the locations explain 65.5% of the variation in HI, genotypes 21.5% (Table 2.3).

Table 2.6 Harvest index (HI) of five genotypes at different locations in Asia (average of 2001 and 2002).

Location	Genotype					
	TA[a]	IR	NP	NI	TE	Average
Iwate	0.42 bc[b]	0.27 b	0.20 b	0.33 b	0.30 b	0.31
Nagano	0.55 ab	0.45 a	0.38 a	0.49 a	0.49 a	0.47
Kyoto	0.56 ab	0.50 a	0.46 a	0.41 ab	0.40 ab	0.46
Shimane	0.52 ab	0.48 a	0.41 a	0.42 ab	0.41 ab	0.45
Nanjing	0.60 a	0.51 a	0.42 a	0.53 a	0.45 ab	0.50
Taoyuan	0.50 ab	0.48 a	0.42 a	0.42 ab	0.36 ab	0.44
Chiangmai	0.44 b	0.38 ab	0.35 a	0.34 b	0.34 b	0.37
Ubon	0.28 c	0.28 b	0.15 b	0.35 ab	0.35 ab	0.28

[a] See Table 1 for explanation of acronyms

[b] Within a column, values followed by different letters (a-e) are significantly different at 0.05 probability level.

Response to temperature

We used a similar polynomial equation as in Section 2.3.2 to describe the relation between HI and ATR (Table 2.5). Parameter s is constant for all genotypes (s = -0.006), indicating constant relative decline in HI per degree temperature difference from optimum ATR. ATR_{max} for the indica genotype IR and the indica-japonica crossbred TA is higher than that for the japonica genotype TE, *i.e.* maximum HI of the japonica is attained at lower ATR. The model suggests that HI under optimum ATR could have been about 0.1 higher than in the experiments (Table 2.3).

2.3.5 Protein content

Average protein content varied from 7.0 to 8.5% (Table 2.3), with the highest value for the indica-japonica crossbred TA and the lowest for the indica-javanica crossbred NP. Protein contents were not significantly different among locations, suggesting that environmental factors, *e.g.* temperature and radiation, hardly affected protein content.

2.3.6 Amylose content

Average amylose content varied from 8.5 to 19.9% and differed significantly among genotypes (Table 2.3), with the highest value for IR and the lowest for TA. Amylose content was similar in both years for all genotypes, but significantly different among locations, *i.e.* highest in Iwate and lowest in Chiangmai (Table 2.7), indicating effects of environmental factors. Amylose content increased linearly and significantly with decreasing ATR (Fig. 2.6) for both japonica genotypes and both crossbreds, for IR the the trend was similar but non-significant.

Table 2.7 Grain amylose content (%) of five genotypes at different locations in Asia (average of 2001 and 2002).

Location	Genotype					
	TA[a]	IR	NP	NI	TE	Average
Iwate	12.7 a[b]	21.6 a	15.0 a	15.4 a	15.4 a	16.3
Kyoto	7.7 bc	17.8 c	9.3 bc	9.3 b	10.5 bc	11.1
Shimane	8.7 bc	20.8 ab	9.9 b	10.7 b	10.7 bc	12.1
Nanjing	7.5 c	20.7 ab	9.7 b	7.4 c	10.0 c	11.1
Taoyuan	9.7 b	19.6 bc	10.3 b	9.3 b	11.65 b	12.1
Chiangmai	4.6 d	19.0 c	7.9 c	5.2 d	6.6 d	8.7

[a] See Table 2.1 for explanation of acronyms.

[b] Within a column, values followed by different letters (a-d) are significantly different at the 0.05 probability level.

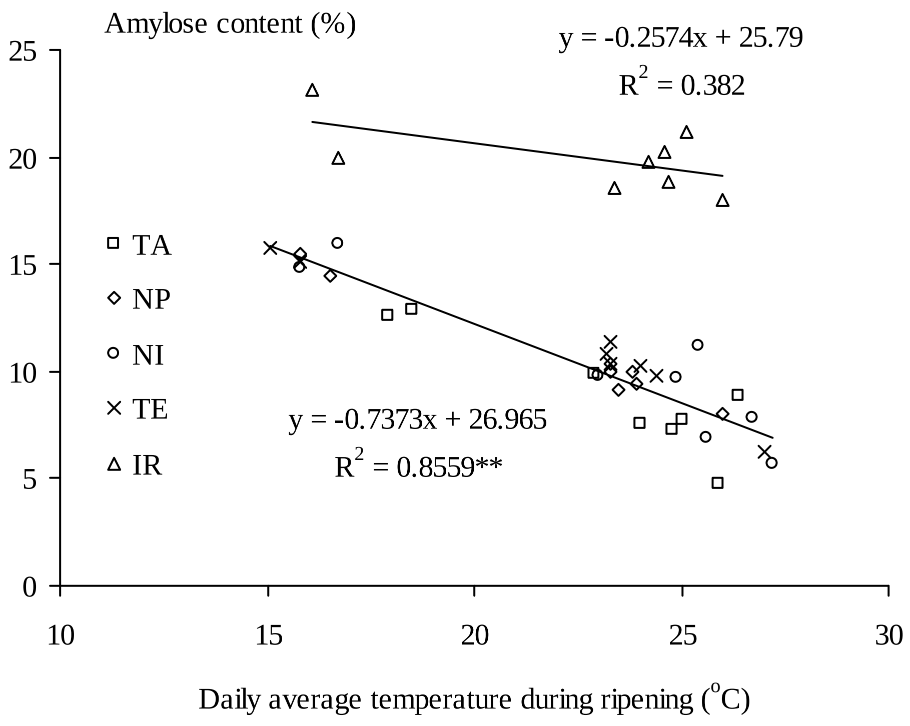


Figure 2.6 Relation between daily average temperature during the ripening phase and amylose content for different genotypes at different locations in Asia. See Table 2.1 for explanation of acronyms.
*** Correlation coefficients significant at 0.01 level.*

2.4 Discussion

2.4.1 Grain yield

About 80% of the observed variation in yield is explained by differences in environmental factors (E), while genotype (G) and interactions (G×E) each contribute 10%. These proportions could change for other combinations of genotypes and environments, but environmental factors contribute most to yield variation of rice grown in tropical and subtropical areas (Dobermann *et al.*, 2003a; Ying *et al.*, 1998a). Therefore, genotype selection for specific environments is an effective strategy to increase rice yields. For example, in Iwate (low temperature), the japonicas NI and TE outyielded the indica IR, while in tropical Chiangmai and Ubon the situation was reverse. Japonica genotypes are tolerant to relatively low temperatures, while indica genotypes perform better under relatively high temperatures. Indica×japonica crossbreds may perform relatively well in both environments, as shown by TA that produced reasonably high yields at both Iwate and Chiangmai (Table 2.4).

The curvilinear relationship between ATR and yield indicates that both low and high temperatures during ripening reduce grain yields (Fig. 2.3). Optimum ATR for realizing maximum yields under the specific management, varied among genotypes: it was highest for the indica IR and the indica×japonica crossbred TA, lowest for the japonica genotypes NI and TE, and intermediate for NP. In contrast to the observed yields, the predicted maximum yields did not differ greatly among genotypes, except for NP with a predicted maximum yield about 1 Mg/ha lower than those of the others.

Average yields at the most northern location, Iwate, and in tropical Chiangmai and Ubon were much lower than at the other (subtropical) locations. The very low yield at Ubon is consistent with other reports (Whitbread *et al.*, 2003; Wonprasaid *et al.*, 1996). Total biomass production is one of the major determinants of yield (Cock and Yoshida, 1972; Murata and Matsushima, 1975). Intercepted PAR provides the energy for the photosynthesis process and thus for the accumulation of biomass. Intercepted PAR at tropical Chiangmai and Ubon was low, as a consequence of short vegetative growth periods (Fig. 2.2), resulting in poor canopy development and low LAI (Oldeman *et al.*, 1987; Yin *et al.*, 1997) and thus poor biomass production (Fig. 2.5). In addition to intercepted PAR, RUE determines biomass production. RUE varied among genotypes and locations. In Taoyuan, highest RUE was observed, up to a maximum of 2.8 g MJ^{-1} as also reported by Sinclair (1998), while in Iwate and Ubon RUE was below 1.7 g MJ^{-1}.

High temperatures during ripening resulted in lower HI in our experiments, because it reduced the ripening duration (Fig. 2.2). Consequently, total biomass accumulation decreased during ripening, leading to low yield. Additionally, high and low temperature during ripening reduced spikelet fertility (Fig. 2.7), resulting in limited sink size (Prasad *et al.*, 2006).

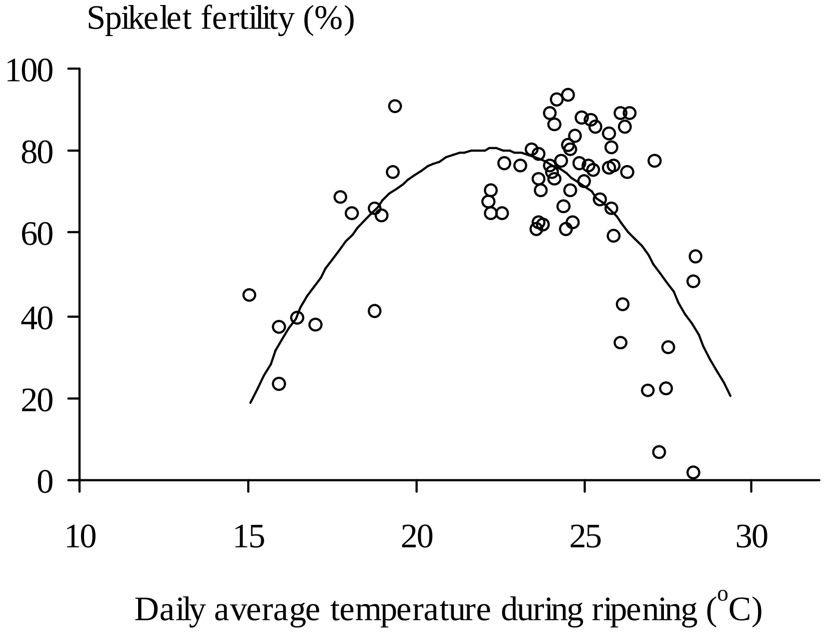


Figure 2.7 Spikelet fertility versus daily average temperature during ripening in rice.

PTQ, 30 days prior to anthesis was closely correlated with yield. Japonica genotypes produced less yield per unit development time than indica and crossbred genotypes. The lower japonica yields are associated with lower spikelet numbers per unit per developmental time than indica or crossbred (Fig. 2.8, Islam and Morison, 1992), suggesting limited sink size of japonica.

In addition to temperature and radiation, the yield-determining factors, yield variation may be associated with differences in yield-limiting factors, as determined by soil characteristics (Van Ittersum and Rabbinge, 1997). Especially indigenous soil nitrogen supply strongly varies across Asian agro-ecosystems (Dobermann *et al.*, 2003a). The effect of indigenous soil N supply on yields decreases with N fertilizer application (Jing *et al.*, 2007). In the experiments, N fertilizer supply was about 1 kg N ha^{-1} d^{-1}, restricting the effect of indigenous soil N supply on crop production. The influence of different soil characteristics on yield could be further explored using simulation models. Well-calibrated and validated models synthesize current knowledge on physiological and ecological crop growth processes, and can help to improve our insight in relationships between indigenous soil N supply and crop performance.

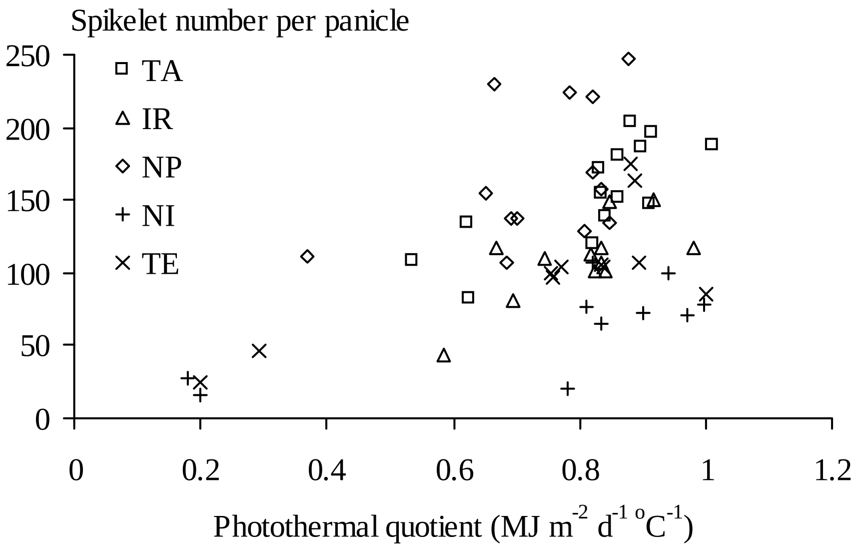


Figure 2.8 Spikelet number per panicle versus photothermal quotient in rice. See Table 2.1 for explanation of acronyms.

2.4.2 Grain quality

Protein content showed small but significant differences among the genotypes, ranging from 7 to 8%, which is within the range of 4 to 14% found in a selection of Asian rice genotypes (Juliano and Villareal, 1993). Protein content of rice is mainly affected by N management (Borrell *et al.*, 1999; Perez *et al.*, 1996), which explains the small differences in this study, where N management was rather uniform.

In contrast, amylose content of rice grain significantly varied among the genotypes in our study. Differences in genotype accounted for more than 70% of the total variability in observed amylose contents. According to the amylose classification of rice genotypes (Juliano, 1979, 1985), IR belongs to the low (12-20%) amylose genotypes, the other genotypes belong to the very low (2-12%) amylose types. Our results are in line with this classification, since IR had clearly the highest amylose content (20%) while that of the other genotypes varied between 8 and 11%. In addition to genotypical differences, amylose content varied significantly across experimental sites: At Iwate amylose contents were highest, while at Chiangmai they were generally lowest. This confirms the qualitative assessment by Juliano (1998), suggesting lower amylose contents at higher temperatures during ripening. Umemoto *et al.* (1995) reported higher amylose contents with lower temperatures during the ripening phase, due to higher activity of the granule-bound starch synthase in the endosperm. In our study, temperatures during ripening were lowest in Iwate and highest in Chiangmai, suggesting that temperature is an important environmental factor in amylose formation. Overall, amylose content of all genotypes was linearly and inversely correlated to temperature during the ripening stage (Fig. 2.6). The close relationship between amylose content and temperature during ripening, in addition to the genotypic amylose traits, suggests that amylose content of rice can be predicted with reasonable accuracy.

2.5 Conclusions

Differences in rice yields under given management are mainly the consequence of differences in environmental conditions and much less of differences in genotypic characteristics. Yields in tropical areas are generally lower than in sub-tropical regions, as a consequence of both, low biomass production and low HI. In tropical areas, characterized by high temperatures, crop phenological development during the vegetative phase is fast, resulting in poor leaf area development, restricting radiation interception and length of the ripening phase limited, leading to lower HI. For tropical areas, genotypes are required that rapidly develop a ‘leafy’ canopy in the vegetative stage. Low temperatures, as in Iwate, also may restrict biomass production due to low RUE and low HI associated with spikelet sterility, *i.e.* sink limitation. The high RUE at Taoyuan in combination with the high radiation levels, resulted in very high grain yields.

PTQ, 30 days prior to anthesis correlates well with grain yield, suggesting a a major effect of pre-anthesis growing conditions on yield formation.

In contrast to yield, genotypic characteristics contribute most to the variation in amylose content of rice grains. This indicates that genotype selection is required in targeting specific grain quality characteristics. In addition, crop management, especially with respect to sowing date, may be adapted to realize a targeted grain amylose content, as temperature is an important controlling factor in amylose formation.

Overall, these multi-location trials have yielded a substantial amount of new information and data sets to calibrate, validate and improve existing rice simulation models. The experiments especially provide information on quality relationships of rice grain, that could be incorporated in simulation models. In addition, the study contributes data sets for further analysis of genotype-environment-management (G×E×M) interactions, for example, with respect to nitrogen management.

3 Analysis of environmental factors affecting yield and N uptake of irrigated rice in Asia using a modelling approach

Qi Jing[1,3,4], Bas Bouman[2], Herman van Keulen[3,4], Huib Hengsdijk[3], Weixing Cao[1], Tingbo Dai[1]

[1] Hi-Tech Key Lab of Information Agriculture of Jiangsu Province, Nanjing Agricultural University, Nanjing 210095, China
[2] International Rice Research Institute, Los Baños, Philippines
[3] Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA Wageningen, the Netherlands
[4] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, the Netherlands

Abstract

Rice yield is the result of the interaction between genotype (cultivar characteristics), environment (climate and soil conditions), and management. Few studies have attempted to isolate the contribution of each of these factors. In this study, the rice growth model ORYZA2000 has been applied to analyze the variation in yield, N uptake, and internal N use efficiency (INUE, grain yield per unit total crop N uptake) of rice in different environments in Asia, and to identify the relative contribution of indigenous soil N and external N supply and of the weather factors temperature and radiation to observed variation. The model was calibrated and evaluated using a large empirical data set that spanned three contrasting varieties, eight locations, and three years in Asia.

ORYZA2000 satisfactorily simulated crop biomass, yield, N uptake, and INUE, that strongly varied among genotypes and locations. Environmental factors contributed differentially to yield, N uptake, and INUE, and their contributions were modified by N management. Indigenous soil N supply affected yield and INUE stronger than weather conditions at low fertilizer N rate, and its effect was less pronounced at high fertilizer N rate. Under both low and high fertilizer N rates, indigenous soil N supply affected N uptake more strongly than weather conditions. Temperature contributed more than radiation to the variation in yield, N uptake, and INUE. Results suggest that N fertilizer management should take into account indigenous soil N supply, while temperature is the primary factor for selection of genotypes and sowing dates in rice production.

Key words: rice; indigenous soil N supply; temperature; radiation; model; Asia.

3.1 Introduction

Irrigated rice fields in Asia contribute about 70% to global rice production and provide the staple food to nearly half the world's population (Bouman *et al.*, 2007). Yields need to increase to meet the increasing demand for rice associated with a growing population (Khush, 2005). Rice yields vary strongly across Asia, from less than 2000 kg ha^{-1} to more than 15000 kg ha^{-1} (Horie *et al.*, 1997; Romyen *et al.*, 1998; Whitbread *et al.*, 2003; Ying *et al.*, 1998a), depending on location and variety. Yield is the result of the interaction between genotype (cultivar characteristics), environment (climate and soil conditions), and management (Cooper *et al.*, 1999; Horie *et al.*, 1997; Wade *et al.*, 1999). Insight into the relative importance of these factors is important to identify improved crop management practices and/or design new varieties to increase yield and resource use efficiency, for instance for nitrogen (N). Dobermann *et al.* (2003a) reported yields from different locations in Asia, ranging from 3600 to 5300 kg ha^{-1} for local varieties without external nutrient inputs, that were probably limited by indigenous soil N supply (Cassman *et al.*, 1998). The effect of N fertilization is variety-specific (Tang *et al.*, 2007; Van Keulen, 1977) and depends on climatic conditions. Horie *et al.* (1997) and Ying *et al.* (1998a) demonstrated that, with sufficient N supply, yields were 40% higher in subtropical areas than in tropical areas. The efficiency with which plants use N to produce grains, varies with environment and variety (Van Keulen, 1977). Internal N use efficiency (INUE), defined as yield per unit total N uptake (kg grain kg^{-1} N), varied across Asia from 23 to 121 (Hossain *et al.*, 2005; Peng *et al.*, 2006; Witt *et al.*, 1999; Ying *et al.*, 1998b).

Many studies have attributed the variation in yield and crop response to N fertilizer in general terms to differences in varietal characteristics and environmental conditions, but few attempts have been made to systematically disentangle the contributions of each factor. It is difficult to design field experiments aiming at isolating environmental factors, because they are often beyond the experimenter's control and because they interact during crop growth. Moreover, field experiments are costly and labour-intensive, and multi-annual, multi-location experiments would be required. Simulation models, which are simplified representations of a complex reality, are useful tools to explore and disentangle effects of interacting factors on crop growth and development (Bouman *et al.*, 1996). Field experiments can be mimicked by changing genetic, environmental, or management input parameters that are completely under the control of the model user. A requisite for any model use, however, is that the model is well calibrated and evaluated for the intended target area and the intended purpose.

In this study, we use the rice growth model ORYZA2000 (Bouman *et al.*, 2001) to analyze the variation in yield, N uptake, and INUE of rice in different environments in Asia, and to identify the relative contribution of indigenous soil N supply and the weather factors temperature and radiation to the observed variation. The model was first calibrated and evaluated on the basis of a large empirical data set, comprising three varieties, eight locations, and three years in Asia.

3.2 Materials and methods

3.2.1 Methodological framework

We used data from field experiments at different sites in Asia to calibrate and evaluate the crop growth model ORYZA2000. Next, ORYZA2000 was used to simulate yield, N uptake, and INUE in scenarios with varying fertilizer N rates, indigenous soil N supply rates, temperature and radiation regimes. Scenario results were analyzed to identify the contribution of each of the management and environmental factors to the variation in yield, N uptake, and INUE.

3.2.2 Field experiments

The experiments were carried out in 2001 and 2002 at Iwate (39° 21′ N, 141° 13′ E), Nagano (35° 51′ N, 138° 10′ E), Shimane (35° 30′ N, 132° 36′ E), and Kyoto (35° 1′ N, 135° 45′ E) in Japan, at Nanjing (32° 6′ N, 118° 45′ E) in China, and at Chiangmai (18° 47′ N, 98° 59′ E) and Ubon Ratchathani (15° 20′ N, 104° 52′ E) in Thailand, and in 2002 and 2003 at Taoyuan (26° 16′ N, 101° 2′ E) in Yunnan Province, China.

Three rice varieties, representing major genotypes, were grown at all sites: the *indica* variety IR72, the *japonica* variety Nipponbare, and the *indica*×*japonica* crossbred Takanari (only IR72 was not grown at Taoyuan in 2003). All experiments were laid out in a randomized block design with 3 replicates and a plot size of 20 m^2. At transplanting, 40 kg N ha^{-1} was applied while 20 kg N ha^{-1} was top-dressed at 20-day intervals, starting from 20 days after transplanting until 10 days after heading.

Total N rates varied from 100 to 160 kg ha^{-1}, depending on actual growth duration of the crops. In addition to N, 120 kg P_2O_5, and 120 kg K_2O ha^{-1} were applied as basal dressing in all fields, including the control plots (0 N). Rice seedlings with 4-5 leaves were transplanted at 15 x 30 cm spacing, with one seedling per hill in 2001 and two seedlings per hill in 2002 and 2003. All fields were continuously submerged throughout the growing season. Weeds, pests, and diseases were adequately controlled by biocides. At each site, IR72 was also grown in control plots, with the same management, except for the omission of fertilizer N.

Dates of sowing, emergence, transplanting, panicle initiation, flowering, and maturity were recorded. For each variety, 20 plants were harvested at transplanting, and eight hills at 20 days after transplanting, panicle initiation, two weeks before flowering, flowering, two weeks after flowering, and maturity. Green leaf area was measured and leaf area index (LAI) calculated. Weights of green leaves, dead/yellow leaves, stems (including leaf sheaths), and panicles were determined after oven drying at 80 °C till constant weight. N content of the crop components was determined by near-infrared spectroscopic analysis (BRAN+LUEBBE, Infra-Alyzer500 equipped with IDAS software) and calibrated by the value obtained by the Kjeldahl method (not at Taoyuan in 2003). At maturity, grain yield was measured from 2 m^2 and expressed at 14% moisture content. Due to experimental errors, yields were not available for Nipponbare at Ubon and for IR72 in 2001 at Iwate, and in 2002 at Nagano; final crop biomass was not available for Nipponbare at Ubon and for IR72 in 2001 at Iwate; total N uptake was not available for any variety at Nagano, for Nipponbare in 2001 at Iwate, and for Takanari in 2002 at Ubon. Throughout the growing season, daily maximum and minimum temperatures and solar radiation were recorded at weather stations installed at/near the sites.

N uptake by the crop and its components was calculated from dry weight and N contents. Internal N use efficiency was calculated by dividing grain yield by total crop N uptake (following Witt *et al.*, 1999).

GenStat for Windows 8th Edition (http://www.vsn-intl.com/genstat/) was used in the analysis of variance of yield, N uptake, and INUE using the method of residual maximum likelihood (REML; Welham and Thompson, 1997).

3.2.3 The ORYZA2000 model

ORYZA2000 is a dynamic, ecophysiological crop model (Bouman *et al.*, 2001) originating in the ‘School of De Wit’ (Bouman *et al.*, 1996; Van Ittersum *et al.*, 2003). It simulates, with time steps of one day, growth and development of rice for potential, water-limited, and N-limited production situations (Van Ittersum and Rabbinge, 1997). For all production situations, optimal control of diseases, pests, and weeds is assumed.

In ORYZA2000, under optimal crop management, light and temperature are the main factors determining crop growth. The light profile within the canopy is calculated from total leaf area and its vertical distribution. When the canopy is not yet closed, leaf area development is calculated from mean daily temperature, and after closure from the increase in leaf weight, using a development stage-dependent specific leaf area. On the basis of single leaf photosynthetic characteristics, defined as a function of incident radiation, air temperature, and leaf N concentration, instantaneous canopy photosynthesis rates are calculated for pre-defined combinations of time-of-day and depth-in-the-canopy. Integration over total leaf area and over the day yields daily total assimilation rate. Daily dry matter accumulation is calculated by subtraction of maintenance and growth respiration requirements. The dry matter increment is partitioned among the various plant organs as a function of phenological development stage, which is tracked as a function of mean daily air temperature. Spikelet density at flowering is derived from total dry matter accumulation over the period from panicle initiation to flowering.

Total daily demand for N is calculated from dry weights, growth rates and N concentrations of the various plant organs. The basic assumption is that the crop aims at maintaining ‘maximum’ N concentrations in its vegetative organs, defined as a function of phenological development stage. Potential N concentration in the panicle is defined as a constant value, and N demand from the panicles must be satisfied through translocation from the vegetative organs. For leaves and stems, potentially translocatable N is defined as the difference between total N in the organ and an exogenously-defined residual level at maturity. Roots contribute a fixed fraction of the combined N translocation from leaves and stems. Actual crop N uptake is restricted by a maximum physiological uptake rate of the plant and available mineral N in the soil. Available soil N is calculated through a simple bookkeeping routine of both indigenous soil N and fertilizer N, without simulating the dynamics of N transformation processes in the soil. Indigenous supply is defined as a constant daily rate. Available fertilizer N is calculated as application rate multiplied by a potential (or maximum) recovery fraction, defined as a function of crop development stage, with relatively low values at transplanting and high values at panicle initiation. Seasonal-average fertilizer N recovery thus depends on the day-to-day balance between supply (timing of fertilizer application) and crop demand. Leaf N concentration affects leaf photosynthesis rate and leaf expansion rate, while the total amount of N in the crop affects the rate of leaf senescence after flowering.

ORYZA2000 was calibrated and evaluated under potential and N-limited conditions in the Philippines (Bouman and Van Laar, 2006) and in China (Jing *et al.*, 2007), and under potential and water- and N-limited conditions in Indonesia (Boling *et al.*, 2007) and China (Belder *et al.*, 2007; Feng *et al.*, 2007). Following Bouman and Van Laar (2006), we parameterized ORYZA2000 for each variety, using the experimental data from all sites in 2002 (calibration set). Phenological development rates were calculated from daily air temperatures and the recorded dates of emergence, panicle initiation, flowering, and maturity. Specific leaf area was computed from measured green leaf area and green leaf dry weight. Dry matter partitioning factors were first estimated from measured biomass of leaves, stems, and panicles, and further fine-tuned by matching simulated and measured values of LAI and biomass of crop organs. All other crop parameters were set to the values from ORYZA2000's standard IR72 crop data file (Bouman *et al.*, 2001). For each site, indigenous soil N supply was first estimated from N uptake by the crop in the omission plots, and subsequently fine-tuned by matching simulated and measured values of crop N uptake. Since N uptake in omission plots was only measured at Shimane, Kyoto, Ubon, Taoyuan, and Kyoto, we used the estimated values at Kyoto also for Iwate and Nagano, and the estimated values at Ubon for Chiang Mai. Indigenous soil N supply at Nanjing was derived from a nearby experiment (Jing *et al.*, 2007; Jing *et al.*, 2005). A complete list of all model input parameter values is available from the authors.

The performance of ORYZA2000 was evaluated separately for the calibration set of 2002 and for the separate validation data sets of 2001 and 2003 (for Taoyuan). Following procedures developed by Bouman and Van Laar (2006), we graphically compared simulated and measured biomass and N uptake of the whole crop and of the panicles, and grain yield. For the same variables, we computed the slope (α), intercept (β), and coefficient of determination (R^2) of the linear regression between simulated (Y) and measured (X) values. We also calculated the Student's t-test of means assuming unequal variance (P (t)), and the absolute ($RMSE_a$) and normalized ($RMSE_n$) root mean square errors between simulated and measured values:

$$RMSE_a = \left(\frac{\sum (Y_i - X_i)^2}{n} \right)^{0.5} \qquad \text{(eqn 3.1)}$$

$$RMSE_n = \frac{100 \times RMSE_a}{\sum X_i / n} \qquad \text{(eqn 3.2)}$$

where *n* is the number of observations.

A model reproduces experimental data best when α is close to 1, β close to 0, R^2 close to 1, P (t) larger than 0.05, $RMSE_a$ similar to the standard error (SE) of measured values, and $RMSE_n$ similar to the CV of measured values. We calculated the SE and CV of measured crop variables as averages over all experiments at all sites (per experiment, SE and CV are calculated from the three replicates) (Table 3.1). We compared our evaluation results with those presented in literature for ORYZA2000.

Table 3.1 Standard error (SE, the same unit as variable) and coefficient of variation (CV) for measured crop variables in the field experiments.

Crop variable	N	SE	CV (%)
During growing season			
Aboveground biomass (kg ha^{-1})	237	520	7
Biomass of panicle (kg ha^{-1})	125	335	9
N in crop (kg ha^{-1})	215	9	9
N in panicle (kg ha^{-1})	94	5	8
At harvest			
Aboveground biomass (kg ha^{-1})	46	883	6
Yield (kg ha^{-1})	44	294	5
N in crop (kg ha^{-1})	42	12	7

N is number of data in experiments.

3.2.4 Scenario analysis

Ten scenarios were constructed, varying in fertilizer N management and in the environmental factors indigenous soil N supply (s), solar radiation (r), and temperature (t) (Table 3.2). In each scenario, ORYZA2000 was run for all three varieties for the experimental weather conditions from both years at each site. In scenarios I-V, the fertilizer N rate was 80 kg ha^{-1}, applied in two equal splits. In scenario I ($F_{s,r,t}$), we used the site-specific indigenous soil N supplies and the site-specific weather conditions (temperature and solar radiation). In scenario II (F_s), we used the site-specific indigenous soil N supplies, but used the weather conditions from Taoyuan in 2002 (where the highest rice yields were recorded; see Results section) for all sites. In Scenario III ($F_{r,t}$), we used an indigenous soil N supply of 0.7 kg ha^{-1} d^{-1} for all sites, combined with site-specific weather conditions. The value of 0.7 kg ha^{-1} d^{-1} is an estimated average for tropical and subtropical areas in Asia (Dobermann *et al.*, 2003a, b; Ten Berge *et al.*, 1997). In Scenario IV (F_t), we again used an indigenous soil N supply of 0.7 kg ha^{-1} d^{-1} for all sites, but replaced in the weather conditions the site-specific radiation data with those from Taoyuan in 2002. Scenario V (F_r) was similar to scenario IV, but using temperatures instead of radiation from Taoyuan in 2002. Scenarios VI-X were similar to scenarios I-V, but with a fertilizer N rate of 160 kg ha^{-1}.

Table 3.2 Scenario specifications for N fertilization and environmental factors.

Scenario	Environmental factor	N fertilization (kg ha^{-1})	Indigenous soil N supply	Radiation	Temperature
I	$F_{s,r,t}$	40, 40	SS	SS	SS
II	F_s	40, 40	SS	U	U
III	$F_{r,t}$	40, 40	U	SS	SS
IV	F_t	40, 40	U	U	SS
V	F_r	40, 40	U	SS	U
VI	$F_{s,r,t}$	80, 80	SS	SS	SS
VII	F_s	80, 80	SS	U	U
VIII	$F_{r,t}$	80, 80	U	SS	SS
IX	F_t	80, 80	U	U	SS
X	F_r	80, 80	U	SS	U

$F_{s,r,t}$ defines the combination of environmental factors, with the subscripts referring to indigenous soil N supply (s), radiation (r), and temperature (t). SS, Site-Specific; U, Uniform among locations, *i.e.* radiation and temperature from Taoyuan, or a constant soil indigenous N supply of 0.7 kg ha^{-1} d^{-1}.

We compared simulated yield, N uptake, and INUE among the scenarios and N rates. First, scenarios F_s and $F_{r,t}$ were compared with $F_{s,r,t}$ to examine the effect of weather (both temperature and radiation) and indigenous soil N supply, respectively. Next, we compared scenarios F_t and F_r with $F_{r,t}$ separately to examine the effect of temperature and radiation, respectively. We computed the slope (α), intercept (β), and coefficient of determination (R^2) of the linear regression, and the Student's t-test of means and the absolute ($RMSE_a$) and normalized ($RMSE_n$) root mean square errors for the yield, N uptake, and INUE between the two scenarios in each comparison.

3.3 Results

3.3.1 Field experiments

Temperatures during the rice growing periods at the different experimental sites (Fig. 3.1) were relatively low at the beginning and end of the growing season at Iwate, Nagano, Kyoto, Shimane, and Nanjing, while they were relatively constant at Taoyuan, Chiangmai, and Ubon. Temperatures were lowest at Iwate, with minima below 20 and maxima not exceeding 30 °C. At Chiangmai and Ubon, minimum and maximum temperatures were over 20 and 30 °C, respectively. Radiation during the rice growing periods varied among locations (Fig. 3.1), with the lowest average values (14.03 MJ m^{-2} d^{-1}) at Iwate, and the highest values at Nagano (17.92 MJ m^{-2} d^{-1}) and Taoyuan (17.20 MJ m^{-2} d^{-1}).

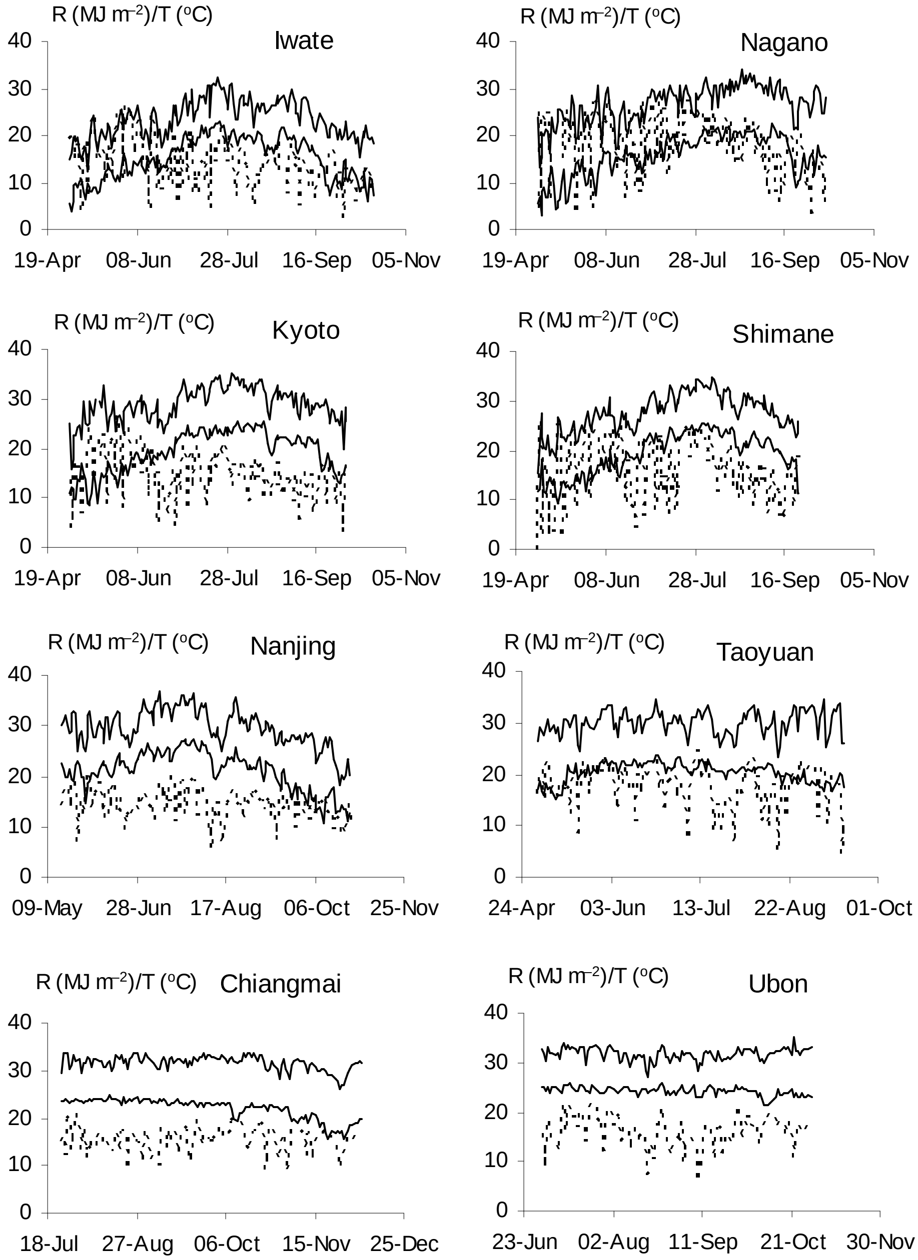


Figure 3.1 Average solar radation (R) and temperature (T) of two years during rice growth at eight locations in Asia. Solid lines are maximum T and minimum T, dotted lines are solar radiation.

Indigenous soil N supply was 0.29 kg ha^{-1} d^{-1} at Ubon, 0.79 at Shimane, 0.90 at Nanjing, 0.92 at Kyoto, and 1.46 at Taoyuan.

Average yields were lowest for Nipponbare and highest for Takanari (Table 3.3). Average yields of the three varieties ranged from 1883 kg ha^{-1} at Ubon to 10224 at Taoyuan, illustrating the strong effect of environmental conditions on yield. The effect of year and the interaction of year by variety was not significant, whereas the interaction of site by variety was significant. The differences in yield among the three varieties were reflected in the differences in N uptake and INUE: highest values for

Takanari and lowest for Nipponbare (though not all differences among varieties were significant). The differences in N uptake and INUE among the sites again illustrate the significant effect of environmental conditions. The sources of variations for N uptake and INUE were the same as for yield.

Table 3.3 The means of yield, total N uptake, and internal N use efficiency (INUE) of three cultivars and the source of variation at eight locations in Asia in two years.

Treatment		Yield (kg ha^{-1})	N uptake (kg ha^{-1})	INUE
Variety (V)	IR72	6663	151	44
	Nipponbare	6074	140	43
	Takanari	7672	156	48
	LSD$_{0.05}$	*333.4*	*8.9*	*3.3*
Location (L)	Iwate	5503	153	36
	Nagano	7831	160	49
	Kyoto	8887	166	54
	Shimane	8554	151	57
	Nanjing	7476	141	53
	Taoyuan	10224	248	41
	Chiangmai	4114	107	37
	Ubon	1883	71	28
	LSD$_{0.05}$	*544.5*	*7.3*	*9.4*
Source of variation				
	Year (Y)	NS	NS	NS
	Y×V	NS	NS	NS
	L×V	**	**	**

**, significant at 0.01 probability level. NS, not significant.

3.3.2 Model evaluation

Simulated biomass of the panicles and of the whole crop agreed quite well with the measured values, in both the calibration and the validation set (Fig. 3.2). Simulated values were also similar to measured values at the 95% confidence level by Student's t-test (Table 3.4). The slope α was usually close to 1 and the intercept β small compared to the mean values. RMSE$_n$ was 16% in the calibration set and slightly higher at 20-24% in the validation set. However, RMSE$_n$ for simulated crop biomass was 2.3 and 2.9 times the CV of the measurements in the calibration set and the validation set, respectively (compare Table 3.1). For panicle biomass, these values were 1.8 and 2.6, respectively.

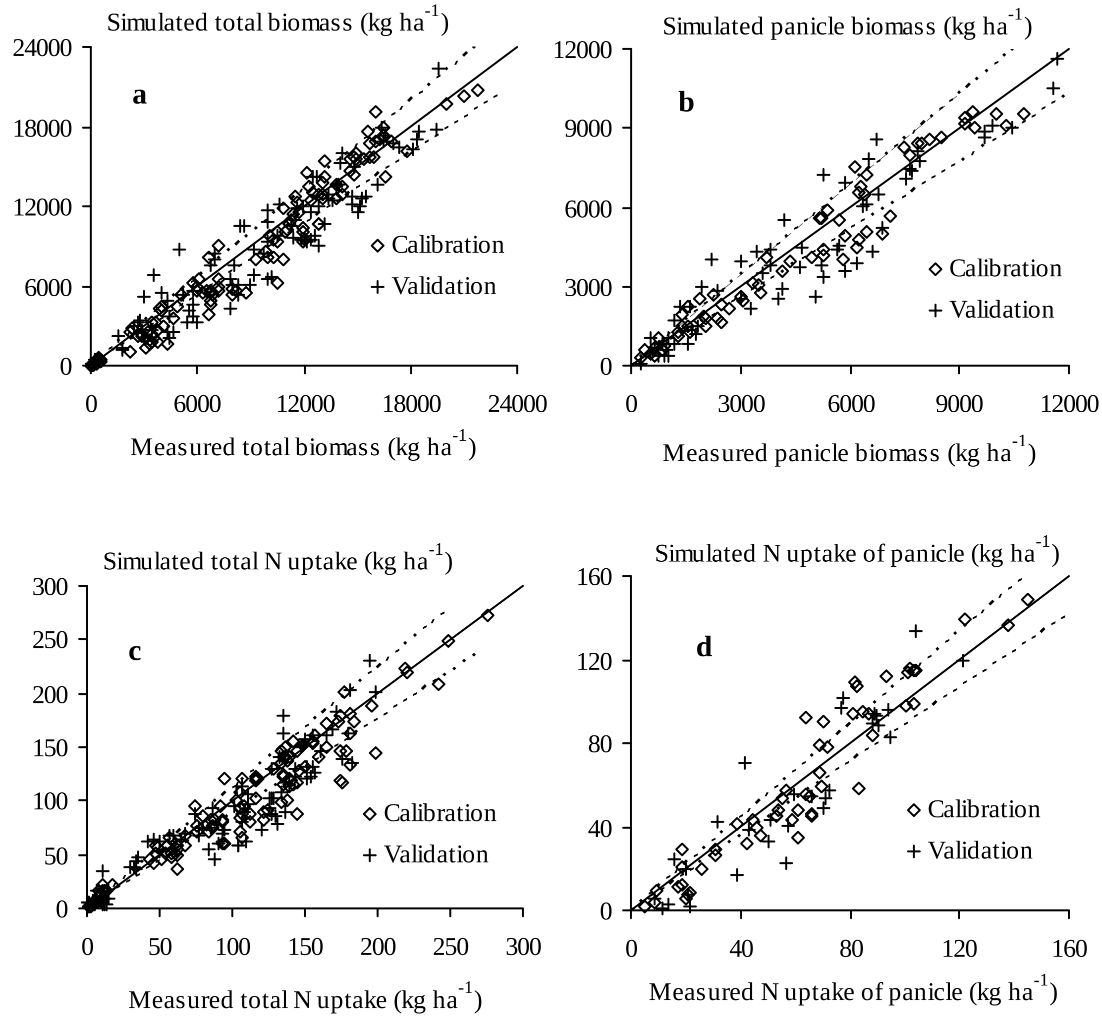


Figure 3.2 Simulated versus measured values of total biomass (a), panicle biomass (b), total N uptake (c), and panicle N uptake (d), for both the calibration and validation set. Solid lines are the 1:1 relationship; dotted lines are plus and minus mean standard deviation of measured values around the 1:1 line.

As for biomass, the data of simulated and measured N uptake by the crop and by the panicles were aligned relatively well along the 1:1 line, in both the calibration and the validation sets (Fig. 3.2). The Student test showed significant correlations between simulated and measured values, and the slopes α of the linear relations were close to 1, with low β values and high coefficients of correlation (Table 3.4). RMSE$_n$ was of the same order of magnitude as for the biomass simulations. RMSE$_n$ for simulated crop N uptake was 2 and 2.7 times the CV in the calibration set and the validation set, respectively. For panicle N uptake, these values were 2.5 and 3.2, respectively.

Table 3.4 Evaluation parameters of ORYZA2000 simulations for dynamic crop growth variables and end-of-season variables for the calibration and validation set.

Crop variable	N	X_{obs} (SD)	X_{sim} (SD)	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$ (%)
Calibration set									
During growing season									
Total biomass (kg ha^{-1})	132	8098 (5705)	7617 (5940)	0.25*	1.020	-641	0.96	1292	16
Biomass of panicles (kg ha^{-1})	65	4534 (2955)	4313 (2948)	0.34*	0.971	-87	0.95	719	16
Crop N uptake (kg ha^{-1})	125	102 (61)	94 (58)	0.15*	0.909	1.5	0.93	18	18
N uptake of panicles (kg ha^{-1})	53	62 (33)	61 (40)	0.46*	1.136	-9.3	0.91	13	20
At harvest									
Final biomass (kg ha^{-1})	24	14815 (4184)	15472 (4142)	0.31*	0.962	1222	0.94	1317	9
Yield (kg ha^{-1})	23	7441 (2510)	7679 (2113)	0.37*	0.800	1724	0.90	839	11
Final N uptake (kg ha^{-1})	23	155 (51)	159 (51)	0.39*	0.978	7.8	0.98	9	6
Validation set									
During growing season									
Total biomass (kg ha^{-1})	105	8419 (5771)	7823 (5599)	0.22*	0.932	-20	0.92	1712	20
Biomass of panicles (kg ha^{-1})	60	4494 (3063)	4191 (2960)	0.29*	0.911	98	0.89	1060	24
Total N uptake (kg ha^{-1})	90	92 (59)	83 (56)	0.16*	0.888	1.6	0.88	22	24
N uptake of panicles (kg ha^{-1})	41	65 (35)	59 (39)	0.26*	1.029	-7.2	0.83	17	26
At harvest									
Final biomass (kg ha^{-1})	22	14645 (4009)	15099 (3217)	0.35*	0.732	4380	0.83	1628	11
Yield (kg ha^{-1})	21	7313 (2505)	7801 (2023)	0.26*	0.727	2482	0.81	1188	16
Final N uptake (kg ha^{-1})	19	133 (43)	142 (48)	0.28*	1.062	1.2	0.93	18	13

N, number of measured/simulated data pairs; X_{obs}, mean of measured values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of population; α, slope of linear relation between simulated and measured values; β, intercept of linear relation between simulated and measured values; R^2, adjusted linear correlation coefficient between simulated and measured values; $RMSE_a$, absolute root mean square error; $RMSE_n$ (%), normalized root mean square error.

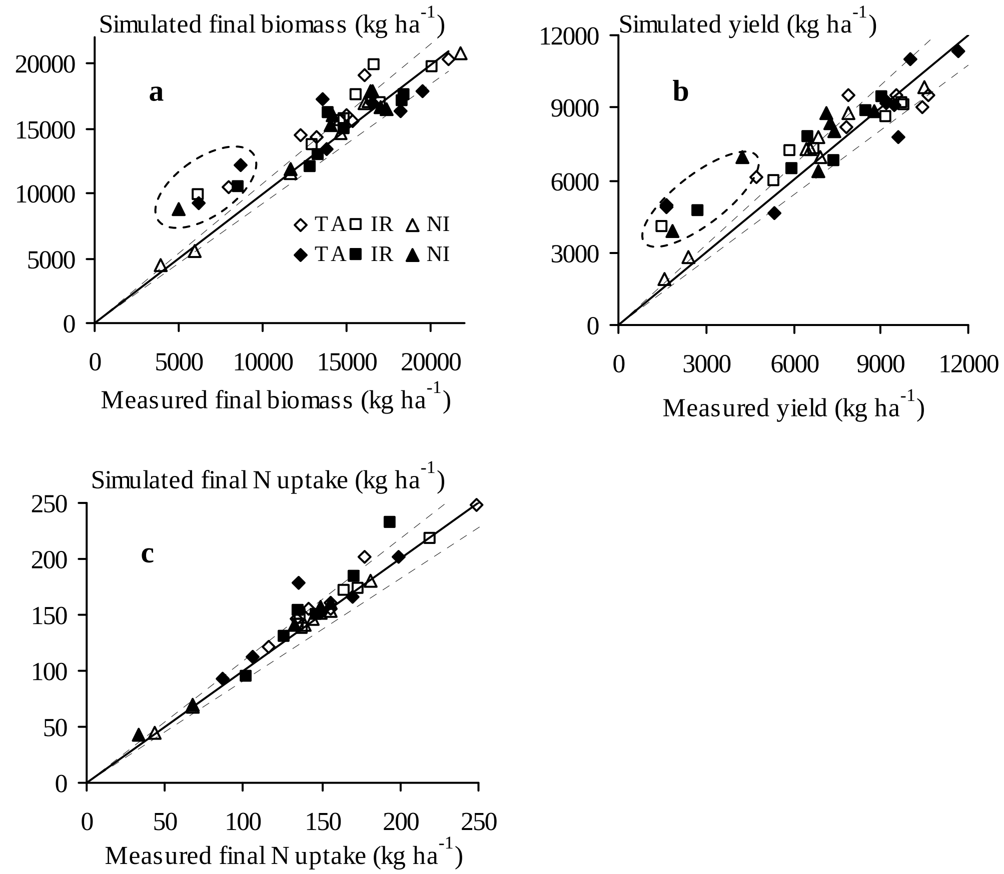


Figure 3.3 Simulated versus measured final total biomass (a), yield (b), and N uptake (c). Open symbols refer to the calibration set, closed symbols to the validation set. Solid lines are the 1:1 relationships; dotted lines are plus and minus mean standard deviation of the measured values. Points in ellipse are from Ubon.

In the comparison of simulated and measured final crop biomass, yield, and crop N uptake, most data points are well aligned around the 1:1 line, in both the calibration and validation sets (Fig. 3.3). In Ubon, both final crop biomass and yield for all three varieties were consistently overestimated in the simulations. The goodness-of-fit parameters confirm the satisfactory performance of the model for all three end-of-season variables (Table 3.4). $RMSE_n$ was only 6-11% in the calibration set and 11-16% in the validation set. Despite these low values, $RMSE_n$ for simulated final crop biomass, yield, and crop N uptake was still 1.5, 2.3 and 0.9 times the CV in the calibration set, respectively, and 1.9, 3.2, and 1.9 times the CV in the validation set.

3.3.3 Scenario analyses

Simulated yield, crop N uptake, and INUE in the scenarios F_s (with site-specific soil N supply and identical weather conditions) and $F_{r,t}$ (with identical soil N supply and site-specific weather conditions) are plotted against the simulated values in scenario $F_{s,r,t}$ (with both, site-specific soil N supply and weather conditions) in Figs 3.4a,c,e with 80 kg fertilizer N ha^{-1}, and in Figs 3.5a,c,e with 160 kg fertilizer N ha^{-1}. The same three variables in the scenarios F_r (with only site-specific radiation and all other conditions identical) and F_t (with only site-specific temperature) are plotted against the simulated values in scenario $F_{r,t}$ (with both site-specific radiation and temperature) in Figs 3.4b,d,f with 80 kg fertilizer N ha^{-1}, and in Figs 3.5b,d,f with 160 kg fertilizer N ha^{-1}. Table 3.5 presents the results of the statistical analysis for all scenario pairs.

Yield. At 80 kg N ha^{-1} (Fig. 3.4a), the yield data of both F_s and $F_{r,t}$ are distributed quite well around the 1:1 line, with comparable values for the goodness-of-fit parameters. At 160 kg N ha^{-1} (Fig. 3.5a), the yield data of $F_{r,t}$ are closer to the 1:1 line (with better values of the goodness-of-fit parameters) than those of F_s. Hence, the level of N fertilizer affected the relative contribution of indigenous soil N supply and weather conditions to the variation in yield: at 80 kg ha^{-1} their effects were of similar magnitude, whereas at 160 kg ha^{-1}, the effect of weather conditions was stronger than that of soil N supply. At both fertilizer levels, the relation $F_{r,t}$ - F_t (Figs 3.4b and 3.5b) had much lower *RMSE*s and higher coefficients of correlation than the relation $F_{r,t}$ - F_r, indicating that temperature had a stronger and more consistent effect on yield than radiation.

N uptake. At both fertilizer N rates, the variation in N uptake in $F_{r,t}$ was much smaller than in F_s (Figs 3.4c and 3.5c). The relation F_s - $F_{s,r,t}$ had a higher correlation coefficient, a slope closer to 1, a smaller intercept, and lower *RMSE* values than the relation $F_{r,t}$ - $F_{s,r,t}$, indicating that indigenous soil N supply contributed more to the variation in N uptake than weather conditions. At both fertilizer N levels, the relation F_t - $F_{r,t}$ (Figs 3.4d, 3.5d) had a slope closer to 1, a smaller intercept, a higher correlation coefficient, and lower *RMSE* values than the relation F_r - $F_{r,t}$, indicating that temperature had a stronger and more consistent effect on N uptake than radiation.

INUE. There was considerable scatter in INUE with relatively low coefficients of correlation and slopes deviating considerably from 1 in the relations F_s - $F_{s,r,t}$ and $F_{r,t}$ - $F_{s,r,t}$ at both fertilizer N rates (Figs 3.4e and 3.5e). At 80 kg N ha^{-1}, indigenous soil N supply and weather conditions had similar effects on the variation in INUE, while at 160 kg N ha^{-1}, weather conditions affected INUE more than soil N supply. At both fertilizer N levels, the relation F_t - $F_{r,t}$ (Figs 3.4f, 3.5f) had a slope closer to 1, a smaller intercept, a higher correlation coefficient, and lower *RMSE* values than the relation F_r - $F_{r,t}$, indicating that temperature had a stronger and more consistent effect on INUE than radiation.

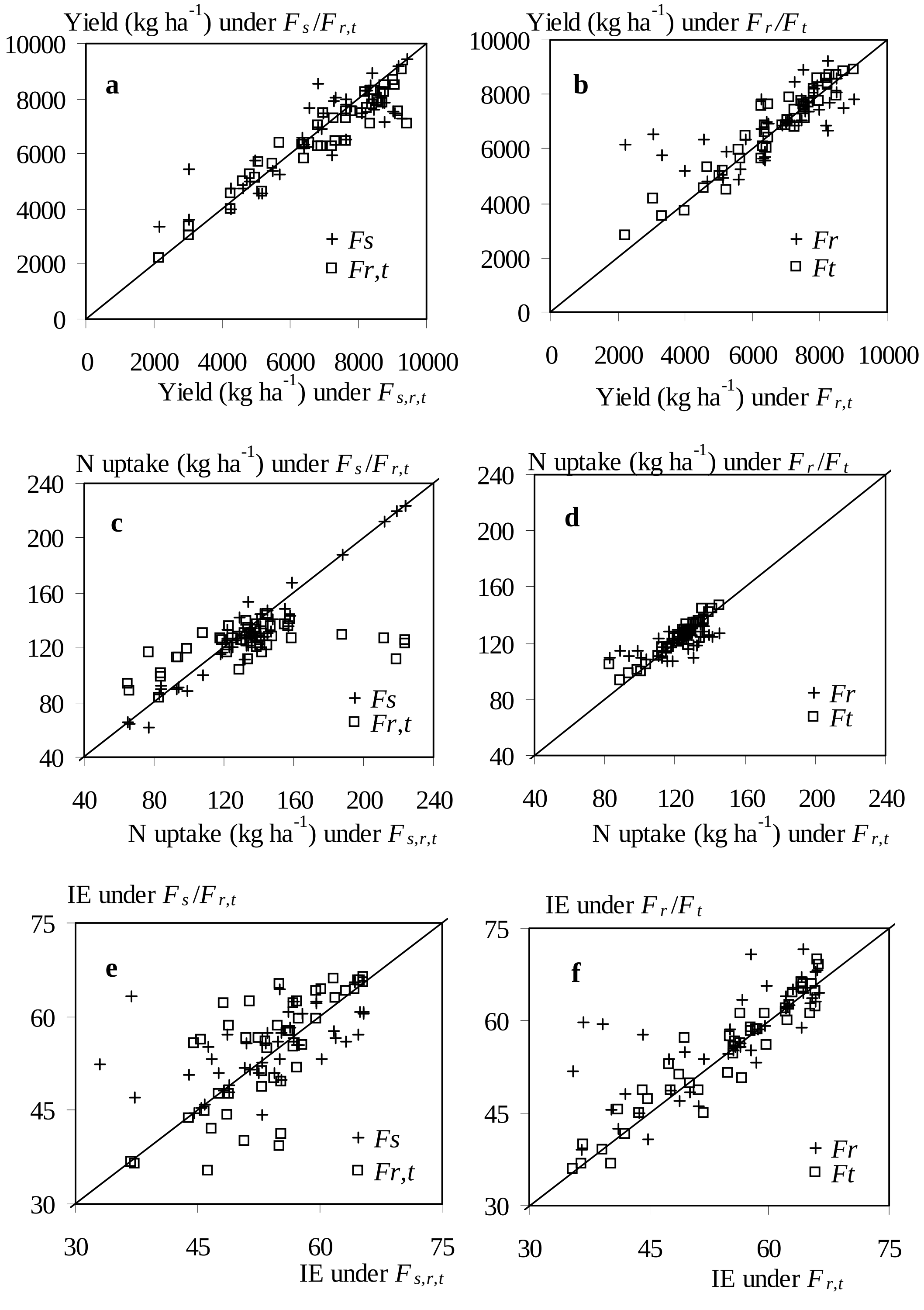


Figure 3.4 Pair-wise comparison of yield (a, b), N uptake (c, d), and internal N use efficiency (IE) (e, f) of scenarios at N rates of 80 kg ha^{-1}. Scenarios are defined in Table 3.2.

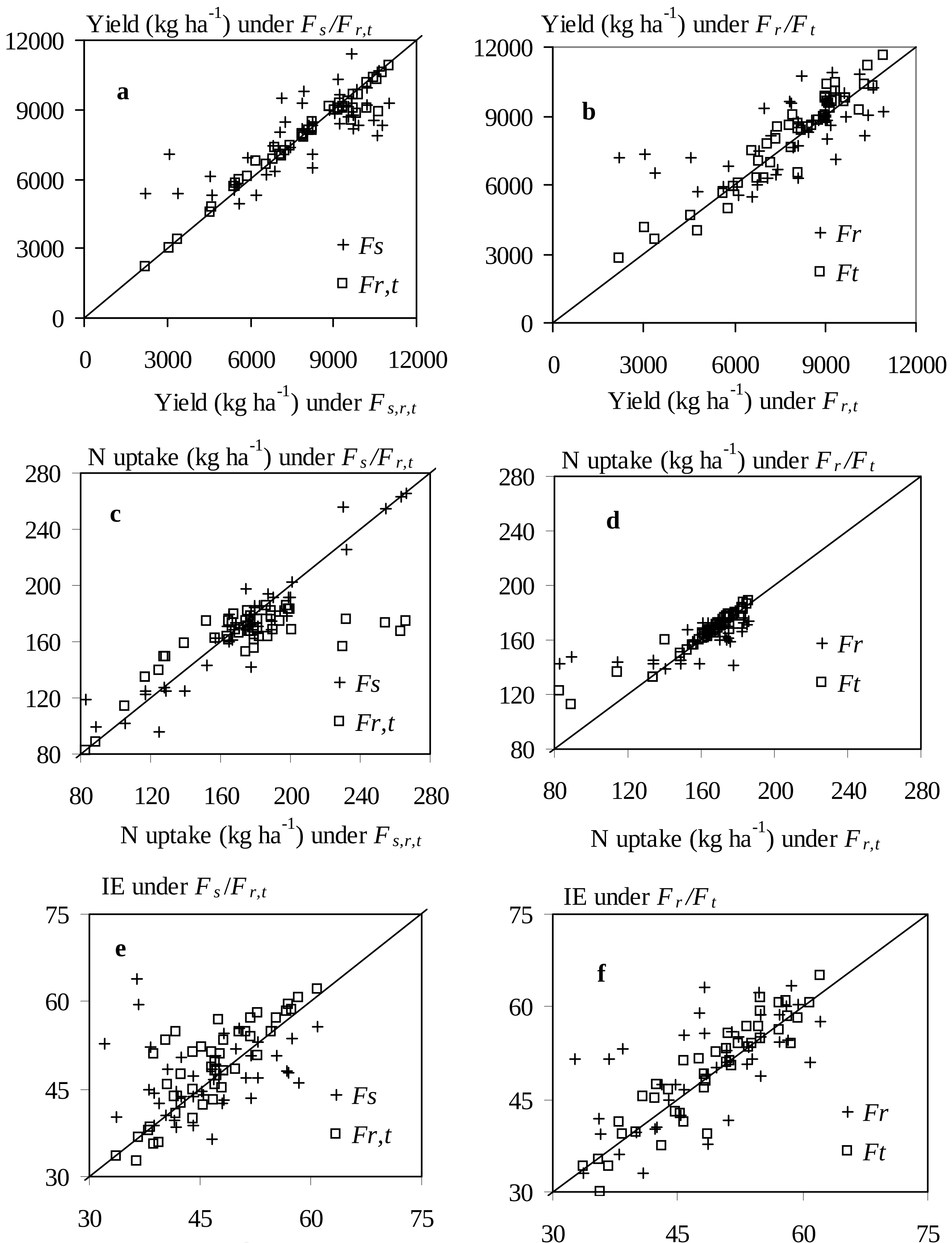


Figure 3.5 Pair-wise comparison of yield (a, b), N uptake (c, d), and internal N use efficiency (IE) (e, f) of scenarios at N rates of 160 kg ha^{-1}. Scenarios are defined in Table 3.2.

Table 3.5 Statistical parameters of pair-wise comparison of scenarios.

N rates	Variable	Scenarios	N	P(t)	α	β	R^2	$RMSE_a$	$RMSE_n$ (%)
80 kg ha^{-1}	*Yield*	$F_{s,r,t}$ - F_s	45	0.396*	1.06	-285	0.80	860	12
		$F_{s,r,t}$ - $F_{r,t}$	45	0.146*	1.13	-483	0.87	813	12
		$F_{r,t}$ - F_r	45	0.214*	0.97	-47	0.48	1141	17
		$F_{r,t}$ - F_t	45	0.313*	0.97	40	0.92	472	7
	N uptake	$F_{s,r,t}$ - F_s	45	0.302*	0.95	10	0.93	9	7
		$F_{s,r,t}$ - $F_{r,t}$	45	0.075*	1.50	-54	0.40	27	22
		$F_{r,t}$ - F_r	45	0.179*	1.23	-26	0.41	11	9
		$F_{r,t}$ - F_t	45	0.255*	1.04	-7	0.94	4	3
	INUE	$F_{s,r,t}$ - F_s	45	0.160*	0.75	13	0.28	7	12
		$F_{s,r,t}$ - $F_{r,t}$	45	0.481*	0.62	21	0.67	6	11
		$F_{r,t}$ - F_r	45	0.049	0.88	3	0.49	8	14
		$F_{r,t}$ - F_t	45	0.398*	0.98	0	0.91	3	6
160 kg ha^{-1}	*Yield*	$F_{s,r,t}$ - F_s	45	0.440*	1.04	-361	0.63	1366	17
		$F_{s,r,t}$ - $F_{r,t}$	45	0.340*	1.10	-602	0.95	579	7
		$F_{r,t}$ - F_r	45	0.206*	0.85	930	0.42	1548	19
		$F_{r,t}$ - F_t	45	0.342*	0.91	583	0.92	653	8
	N uptake	$F_{s,r,t}$ - F_s	45	0.410*	0.94	12	0.90	13	7
		$F_{s,r,t}$ - $F_{r,t}$	45	0.040	1.27	-33	0.51	30	18
		$F_{r,t}$ - F_r	45	0.491*	1.31	-50	0.46	16	10
		$F_{r,t}$ - F_t	45	0.240*	1.26	-45	0.92	8	5
	INUE	$F_{s,r,t}$ - F_s	45	0.100*	0.14	39	0.01	9	19
		$F_{s,r,t}$ - $F_{r,t}$	45	0.120*	0.74	11	0.77	5	10
		$F_{r,t}$ - F_r	45	0.100*	0.67	14	0.36	8	16
		$F_{r,t}$ - F_t	45	0.450*	0.83	8	0.90	3	7

N, number of data pairs; P(t), significance of paired t test; α, slope of linear relation between scenario results; β, intercept of linear relation between scenario results; R^2, adjusted linear correlation coefficient between scenario results; $RMSE_a$, absolute root mean square error; $RMSE_n$ (%), normalized root mean square error.

* means scenario results are the same at 95% confidence level.

See Table 3.2 for definition of scenarios.

3.4 Discussion

Both varietal characteristics and environmental conditions significantly affected crop performance in our experiments, whereas the influence of inter-seasonal variation in local weather conditions (as expressed in the factor ‘year’) was not significant. The difference in performance among varieties supports the notion of “environmental adaptation” of *indica* and *japonica* rice (Morishima and Oka, 1981), which implies that the expression of gene characteristics is influenced by environment(al conditions). Averaged over sites and years, yield, crop N uptake, and INUE were highest for the crossbred Takanari, intermediate for the *indica* IR72, and lowest for the *japonica* Nipponbare.

Averaged over all three varieties and all years, highest yields were obtained at the sub-tropical sites Taoyuan and Kyoto (10224 and 8887 kg ha^{-1}, respectively), and lowest at the tropical sites Ubon and Chiangmai (1833 and 4114 kg ha^{-1}, respectively). Our environments showed large differences in in temperature and solar radiation and in indigenous soil N supply that ranged from 0.29 kg ha^{-1} d^{-1} at Ubon to 1.46 kg ha^{-1} d^{-1} at Taoyuan. The high yields at Taoyuan and Kyoto were the combined result of relatively high levels of solar radiation and low temperatures. The high levels of radiation led to high levels of photosynthesis, whereas the low temperatures led to long crop growth durations, both contributing to large biomass accumulation. At Iwate, temperatures were so low that they limited physiological functioning of rice, resulting in poor and slow vegetative growth, spikelet sterility, delayed heading, and poor grain filling (Lee, 2001). In contrast, the low yields at Ubon and Chiangmai were related to consistently high temperatures that led to relatively short growth durations.

Soils at Taoyuan and Kyoto had the highest levels of indigenous soil N supply, which, in addition to the application of fertilizer N, contributed to high yields (Ying *et al*., 1998a; 1998b). Soil N supply at Ubon was exceptionally low, which may have limited yields. Moreover, the soil at the experimental site at Ubon has been reported to be acidic with soil pH of 4 (Wade *et al*., 1999), which may lead to aluminum/manganese toxicity for rice (Foy, 1984).

ORYZA2000 simulated crop growth variables in our field experiments with comparable accuracies as reported by Bouman and Van Laar (2006), Belder *et al*. (2007), Boling *et al*. (2007), Feng *et al*. (2007), and Jing *et al*. (2007) for lowland rice in Asia (Table 3.6). In our calibration set, RMSE values of simulated biomass, N uptake, and yield were close to or lower than average reported values, whereas in the validation set they were somewhat higher, but still lower than reported maximum values. Despite the large variation in environments and varieties, our yields were simulated especially accurately with a RMSE of 6-13%. Only at Ubon, ORYZA2000 substantially and consistently overestimated yield of all three varieties (Fig. 3.3). Possible yield-reducing effects of the low soil pH and the associated risk for aluminum/manganese toxicity are not taken into account in ORYZA2000. Whereas in literature, reported RMSE values are generally around 1.5-2 times higher than the CV of the measurements, in our experiments they were 0.9-3.2 times higher (with an average of 2.3 over all variables and data sets). One of the reasons is that the CV values in our experiments were relatively low (compared with values in literature), because of the large number of data pairs (N) from all experiments combined. From our evaluation, we conclude that in the validation data set, ORYZA2000 satisfactorily reproduced the measured crop variables relevant for our purpose.

Table 3.6 Absolute ($RMSE_a$) and normalized ($RMSE_n$) root mean square errors of prediction of crop variables for lowland rice by ORYZA2000, as reported in literature.

Crop variable	$RMSE_a$			$RMSE_n$ (%)		
	Mean	Min	Max	Mean	Min	Max
Total crop biomass (kg ha^{-1}) [a]	1148	590	1410	20	13	27
Biomass of panicles (kg ha^{-1}) [a]	710	382	1002	22	14	36
N uptake in crop (kg ha^{-1}) [b]	25	16	30	28	27	28
N uptake in panicles (kg ha^{-1}) [b]	16	12	20	30	30	30
Crop biomass at harvest (kg ha^{-1}) [a]	1434	850	2201	11	7	21
Yield at harvest (kg ha^{-1}) [a]	785	1	1193	13	11	16

[a] Feng *et al*. (2007); Jing *et al*. (2007); Belder *et al*. (2007); Boling *et al*. (2007); Bouman and Van Laar (2006).

[b] Feng *et al*. (2007); Jing *et al*. (2007).

Results of the scenario studies showed that at the fertilizer rate of 80 kg N ha^{-1} effects of indigenous soil N supply and weather conditions (radiation and temperature) on yield were of similar magnitude. At the high external N rate of 160 kg ha^{-1}, the effect of indigenous soil N supply declined, as N-limitation on yield was reduced (Horie *et al*., 1997; Jing *et al*., 2007; Ohnishi *et al*., 1999; Peng *et al*., 2006). In contrast to yield, N uptake increased linearly with N rates exceeding 200 kg ha^{-1} (Jing *et al*., 2007; Ohnishi *et al*., 1999; Peng *et al*., 2006; Peng and Cassman, 1998). In other words, crop N uptake at a fertilizer rate of 160 kg N ha^{-1} was still limited by the availability of N. Indigenous soil N supply is critical in N uptake when external N supply is (relatively) low, as in this study under both N rates of 80 and 160 kg ha^{-1}. The relative effects of indigenous soil N supply and weather on INUE were also affected by N management. At low fertilizer N rate, effects of weather conditions and indigenous N supply on INUE were of similar magnitude, while at high fertilizer N rate the effect of weather conditions on the variation in INUE was relatively stronger. Temperature contributed more to the variation in yield, N uptake, and INUE than radiation. This supports the observation by Ying *et al*. (1998a), that the effect of temperature on growth processes and growth duration is larger than the effect of radiation on photosynthesis.

3.5 Conclusions

The rice simulation model ORYZA2000 performed satisfactorily in simulating yield, N uptake, and INUE of three contrasting varieties at different locations across Asia. The model enabled analysis of the effects of individual factors such as indigenous and external N supply, radiation, and temperature on rice yield, N uptake, and INUE. N supply, radiation and temperature contributed differentially to the variation in simulated yield, N uptake, and INUE. Indigenous soil N supply had a stronger effect on yield and INUE than weather conditions at low fertilizer N rate, while its effect was less pronounced at high fertilizer N rate. Weather conditions and indigenous soil N supply contributed similarly to the variation in N uptake under both low and high N rates. The effect of temperature on yield, N uptake, and INUE was larger than that of radiation. Results of this study indicate that N fertilizer management should take into account indigenous soil N supply, while temperature is the most important factor for genotype selection and for selection of sowing dates for specific sites.

4 Exploring options to combine high yields with high nitrogen use efficiencies in irrigated rice in China

Q. Jing [1, 3, 4], B.A.M Bouman [2], H. Hengsdijk [3], H. van Keulen [3, 4], W. Cao [1]

[1] Key Laboratory of Crop Growth Regulation, Ministry of Agriculture, Nanjing Agricultural University, Nanjing 210095, China
[2] International Rice Research Institute, Los Baños, Philippines
[3] Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA Wageningen, the Netherlands
[4] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, the Netherlands

Abstract

In Jiangsu province, Southeast China, high irrigated rice yields (6-8,000 kg ha^{-1}) are supported by high nitrogen (N) fertilizer inputs (260-300 kg N ha^{-1}) and low fertilizer N use efficiencies (recoveries of 30-35%). Improvement of fertilizer N use efficiency can increase farmers' profitability and reduce negative environmental externalities. This paper combines field experimentation with simulation modelling to explore N fertilizer management strategies to realize high yields, while increasing N use efficiency. The rice growth model ORYZA2000 was parameterized and evaluated using data from field experiments carried out in Nanjing, China. ORYZA2000 satisfactorily simulated yield, crop biomass and crop N dynamics, and the model was applied to explore options for different N-fertilizer management regimes, at low and high levels of indigenous soil N supply, using 43 years of historical weather data.

On average, yields of around 10-11,000 kg ha^{-1} were realized (simulated and in field experiments) with fertilizer N rates of around 200 kg ha^{-1}. Higher fertilizer doses did not result in substantially higher yields, except under very favourable weather conditions when yields exceeding 13,000 kg ha^{-1} were calculated. At fertilizer rates of 150-200 kg ha^{-1}, and at the tested indigenous soil N supplies of 0.6-0.9 kg ha^{-1} d^{-1}, high fertilizer N recovery (53-56%), partial N productivity (50-70 kg kg^{-1}) and agronomic N use efficiency (20-30 kg kg^{-1}) were obtained with application in three equal splits at transplanting, panicle initiation and booting. Increasing the number of splits to six did not further increase yield or improve any of the N use efficiency parameters.

Key words: rice; nitrogen use efficiency; simulation modelling; China.

4.1 Introduction

Rice is one of the most important food crops in China, accounting for about 28% of the total grain-sown area, 43% of total grain production, and 40% of total caloric intake in the country (Huang *et al.*, 2001). China's rice area currently occupies some 30 million hectares, of which 90% is irrigated. Nitrogen (N) is the most important nutrient in irrigated rice production (Cassman *et al.*, 1998) and current high yields of irrigated rice are associated with large applications of fertilizer N (Barker and Dawe, 2001; Pingali *et al.*, 1997). Although N supply drives productivity, low fertilizer N use efficiency is a major characteristic of irrigated rice systems (Cassman *et al.*, 1998). For example, in farmers' fields in Jiangsu, Southeast China, only 30-35% of the fertilizer N is recovered in the rice crop with 260 ~ 300 kg N ha^{-1} applied by farmers (Cui *et al.*, 2000; Peng *et al.*, 2002). Given the low fertilizer N use efficiency, the total use of fertilizer N has to increase substantially in the next decades to increase rice production to meet the food demands of a rapidly growing population (Cassman and Harwood, 1995). Such an increase in fertilizer N use can potentially lead to increased emissions of greenhouse gases (*e.g.*, nitrous oxide) and pollution of water resources. Improving fertilizer N use efficiency of rice will not only reduce these negative externalities, but will also increase the profitability of rice farming (Wang *et al.*, 2001).

Improving fertilizer N use efficiency in many situations also leads to improved utilization of indigenous N resources (Van Keulen, 1982). Indigenous soil N supply originates from mineralization of organic nitrogen, biological N fixation and atmospheric deposition, and is estimated as the N taken up by a crop grown in soil without any N fertilizer (Dobermann *et al.*, 2003a, b). For irrigated rice systems in Southeast China, Dobermann *et al.* (2003a) and Wang *et al.* (2001) reported seasonal values of indigenous soil N supply of 50-116 kg ha^{-1}. To improve fertilizer N use efficiency in rice fields, fertilizer N application rates should be adjusted to indigenous soil N supply. Crop growth simulation models in combination with field experiments are powerful tools to explore such management options. Simulation models synthesize current insights in physiological and ecological crop growth processes, and can help in increasing insight in relationships between indigenous soil N supply, fertilizer N rates, and crop performance. Once a model has been parameterized and validated, it can be used in support of analysis and interpretation of field experiments, for extrapolation of experimental results over a wider range of management practices and weather conditions, and to derive efficient N management strategies (Bouman *et al.*, 1996).

Since the mid-nineties, the International Rice Research Institute (IRRI) and Wageningen University and Research Centre (WUR) have been developing the ORYZA model series to simulate the dynamics of rice growth and development for potential production (Kropff *et al*., 1994a), N–limited (Drenth *et al*., 1994), and water-limited (Wopereis *et al*., 1996) conditions. These models were recently integrated and updated in the model ORYZA2000 (Bouman *et al*., 2001). In this paper, we combine the use of field experiments and ORYZA2000 to assess the effects of indigenous soil N supply and of rates and number of splits of fertilizer N on yield, and to explore options to combine high yields with high N use efficiencies in irrigated rice systems in Southeast China.

4.2 Material and methods

4.2.1 Methodological framework

First, ORYZA2000 was parameterized and evaluated using data from field experiments at Nanjing, Jiangsu province, Southeast China. These experiments included N rates varying from 0 to 405 kg N ha^{-1} in different splits. The performance of ORYZA2000 was appraised by combining various goodness-of-fit parameters and graphical data analysis. Next, ORYZA2000 was used to explore the effects of rate and timing of fertilizer N application, under both low and high indigenous soil N supply, using 43 years of historical weather data. We analyzed the temporal stability of grain yield, and quantified the effects of fertilizer N regimes on yield and N uptake. Various parameters to express the efficiency of N use were quantified and used to identify options to improve N management in rice production.

4.2.2 Experiments

Two field experiments with summer rice (*i.e.* long-duration varieties grown from late spring to early autumn) were carried out in 2001-2002 at Jiangpu experimental station of Nanjing Agricultural University (118.78° E, 32.04° N).

In experiment I, cultivar Wuxiangjing9 was used, a japonica variety widely grown by farmers in Southeast China. In 2001, the experiment was a random plot design, with three replicates and plot sizes of 40 m^2. Four N rates (Table 4.1) were applied as urea, in splits of 55% at transplanting, 5% at tillering, 20% at panicle initiation, and 20% at booting. We applied 60 kg P and 174 kg K ha^{-1} at transplanting. Rice was sown in seedbeds on May 11, and transplanted on June 12 at the rate of two seedlings per hill, spaced 13 cm within the rows and 25 cm between the rows. All treatments were harvested on October 21. Dates of emergence, panicle initiation, booting, heading, and maturity were recorded. Eight hills were harvested from each plot every seven days before the onset of stem elongation and every three days afterwards. The roots were removed and the samples were partitioned in green leaves, yellow/dead leaves, stems, and panicles (after heading). The area of the fresh green leaves was measured using a CI-203 Portable Laser Area Meter until two weeks before maturity and leaf area index (Whitbread *et al*., 2003) was calculated. Samples were oven-dried, first for one hour at 105 ^{o}C and subsequently at 80 ^{o}C for two days to determine dry weights of the plant organs. At maturity, two 1 m^2 areas in each plot were harvested to determine yield. In 2002, the experiment was again a random plot design, with three replicates and plot size of 30 m^2. Five N rates (Table 4.1) were applied as urea in splits of 60% at transplanting, 20% at 15 days after the onset of stem elongation, and 20% 25 days later. We applied 60 kg P and 174 kg K ha^{-1} at transplanting. Rice was sown on May 11, and transplanted on June 15 at the same density and spacing as in 2001. The 0 kg N ha^{-1} plots were harvested on October 5, the 75 kg N ha^{-1} plots on October 15 and the remaining plots on October 21. Phenological development was recorded at tillering, onset of stem elongation, panicle initialization, booting, full heading, 15 days after full heading, 25 days after full heading, and maturity. At these stages, eight hills were harvested from each plot to determine green leaf area and biomass of plant organs, similarly to 2001, but at 25 days after full heading only leaf area was measured. After measuring the dry weights, samples were grounded, and N concentrations determined using the micro-Kjeldahl method, following digestion in a H_2SO_4–H_2O_2 solution. As in 2001, two 1 m^2 areas in each plot were harvested at maturity to determine yield.

Table 4.1 Details of N rates and splits for the field experiments at Nanjing, 2001-2002.

Experiment set	Year	Total fertilizer N rate (kg ha^{-1})	Fertilizer N splits (kg ha^{-1})
Experiment I	2001	0	0
		135	74, 7, 27, 27
		270	148, 14, 54, 54
		405	222, 21, 81, 81
	2002	0	0
		75	45, 15, 15
		150	90, 30, 30
		225	135, 45, 45
		300	180, 60, 60
Experiment II	2001	100	40, 20, 20, 20
	2002	120	40, 20, 20, 20, 20

In experiment II, Wuxiangjing9 was tested in a random plot design with three replicates and plot size of 20 m^2. In 2001, 100 kg urea-N ha^{-1} was applied, 40% at transplanting and the remainder in splits in 20–day intervals following transplanting. All plots received 52 kg P and 100 kg K ha^{-1} at transplanting. Rice was sown on May 12, transplanted on June 13, and harvested on October 1. The experiment was repeated in 2002, with 120 kg urea-N ha^{-1}, 40% at transplanting and the remainder top-dressed in four splits in 20-day intervals. Rice was sown on May 11, transplanted on June 15 and harvested on October 6. Eight hills were harvested from each plot to determine green leaf area, biomass of plant organs, and N concentration, at transplanting, 20 days after transplanting, panicle initiation, two weeks before heading, heading, two weeks after heading, and maturity. At maturity, yield was determined from sample areas, similarly to experiment I.

In both experiments, fields were submerged during the entire growing season. The plots were hydrologically separated by plastic film installed to 30 cm below the soil surface to restrict water and N flows between adjacent plots. All plots were kept free of weeds and received optimal control against pests and diseases. During the experiments, weather data were collected from a weather station 2 km from the experimental site. Historical weather data for the area were obtained from the Meteorological Center of China.

For each measured variable, we calculated mean, standard error (SE) and coefficient of variation (CV). All yields were expressed at 14% moisture content.

4.2.3 The ORYZA2000 model

ORYZA2000 is an ecophysiological crop model (Bouman *et al.*, 2001) of the ‘School of De Wit’ (Bouman *et al.*, 1996; Van Ittersum *et al.*, 2003; Van Ittersum and Rabbinge, 1997; Van Ittersum and Rabbinge, 1997). It simulates, with time steps of one day, growth and development of rice for potential, water-limited and nitrogen-limited production situations. For all production situations, optimal control of diseases, pests, and weeds is assumed. ORYZA2000 was evaluated under potential and nitrogen-limited conditions in the Philippines (Bouman and Van Laar, 2006) and under water-limited conditions in Indonesia (Boling *et al.*, 2007) and China (Belder *et al.*, 2007). A summary description of ORYZA2000 is given here.

Under optimal crop management, light and temperature are the main factors determining crop growth. The light profile within the canopy is calculated from total leaf area and its vertical distribution. When the canopy is not yet closed, leaf area development is calculated from mean daily temperature, and after closure from the increase in leaf weight, using a development-dependent specific leaf area. On the basis of single leaf photosynthetic characteristics, defined as function of incident radiation, air temperature and leaf N concentration, instantaneous photosynthesis rates are calculated for pre-defined combinations of time-of-day and depth-in-the-canopy. Integration over total leaf area and over the day yields daily assimilation rate. Daily dry matter accumulation is calculated by subtraction of maintenance and growth respiration requirements. The dry matter increment is partitioned among the various plant organs as a function of phenological development, which is tracked as a function of mean daily air temperature. Spikelet density at flowering is derived from total dry matter accumulation over the period from panicle initiation to flowering.

Daily demand for N is calculated from dry weights, growth rates and N concentrations of the plant organs. The basic assumption is that the crop strives to maintain ‘maximum’ N concentrations in its vegetative organs (Van Keulen and Seligman, 1987), defined as a function of phenological development stage. Potential N concentration in the panicle is defined as a constant value, and N demand from the panicles must be satisfied through translocation from the vegetative organs. For leaves and stems, potentially translocatable N is defined as the difference between total N in the organ and an exogenously-defined residual level at maturity. Roots contribute a fixed fraction of the combined N translocation from leaves and stems. Actual crop N uptake is limited by a maximum physiological uptake rate of the plant and by the maximum available amount of N in the soil. Available soil N is calculated through a simple bookkeeping routine of both indigenous soil N and fertilizer N, without simulating the dynamics of N transformation processes in the soil. Indigenous supply is defined as a constant daily supply rate. Available fertilizer N is calculated as application rate multiplied by a potential (or maximum) recovery fraction, defined as a function of crop development stage, with relatively low values at transplanting and high values at panicle initiation. Seasonal-average fertilizer N recovery thus depends on the day-to-day balance between supply (timing of fertilizer application) and crop demand.

Leaf N concentration affects the leaf photosynthesis rate and the leaf expansion rate, while the total amount of N in the crop affects the leaf loss rate after flowering.

4.2.4 Model parameterization

We parameterized ORYZA2000 for variety Wuxiangjing9 following the procedure described by Bouman and Van Laar (2006), using the data from experiment I (calibration set). Development rates were calculated using the recorded dates of emergence, panicle initiation, flowering, and maturity and air temperatures. Specific leaf area was computed from measured values of green leaf surface area and green leaf dry weight. Dry matter partitioning factors were first estimated from measured biomass of leaves, stems and panicles, and further fine-tuned by matching simulated and measured values of LAI and of biomass of crop organs. All other crop parameters were set to the values from ORYZA2000's standard crop data file for the tropical high-yielding variety IR72 (Bouman *et al.*, 2001). A complete list of the Wuxiangjing9 parameters is available from the authors.

Indigenous soil N supply was first estimated from crop N uptake in the 0 kg N ha^{-1}–treatment divided by crop growth duration, and further fine-tuned by matching simulated and measured values of crop N uptake.

4.2.5 Model evaluation

The performance of ORYZA2000 was evaluated for the calibration data set (experiment I) and for the independent validation data set of experiment II. Following Bouman and Van Laar (2006), we applied a combination of graphical presentations and statistical measures based on the work and recommendations of Caton *et al.* (1999), Gauch *et al.* (2003), Kobayashi and Salam (2000), and Mitchell (1997). We graphically compared simulated and measured aboveground biomass, grain yield, total crop-N, and leaf N concentration. For the same variables, we computed the slope (α), intercept (β), and coefficient of determination (R^2) of the linear regression between simulated (Y) and measured (X) values. We also calculated the Student's t-test of means assuming unequal variance (P (t)), and the absolute ($RMSE_a$) and normalized ($RMSE_n$) root mean square errors between simulated and measured values:

$$RMSE_a = (1/n\ \Sigma(Y_i - X_i)^2)^{0.5} \qquad \text{(eqn 4.1)}$$

$$RMSE_n = 100\times(1/n\ \Sigma(Y_i - X_i)^2)^{0.5}/\Sigma X_i/n \qquad \text{(eqn 4.2)}$$

where n is the number of observations. The variable X is a mean value of measured yield calculated from the replicates of the field experiment and has a standard error (SE) associated with it. Mostly in model evaluation, any difference between simulated and measured mean values is attributed to model errors, whereas the error in the measured value is not taken into account (*e.g.*, Kobayashi and Salam, 2000; Gauch *et al.*, 2003). However, a model prediction of a certain variable value can not be more accurate than the measurement error of that variable.

A model reproduces experimental data best when α is close to 1, β close to 0, R^2 close to 1, P (t) larger than 0.05, $RMSE_a$ similar to the SE of measured values, and $RMSE_n$ similar to the CV of measured values.

4.2.6 Scenario analysis

Two simulation sets were executed to explore options for combining high yields with high N use efficiencies. In simulation set I, 11 fertilizer N rates (0, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 kg ha^{-1}) were used. At each rate, 50% was applied at transplanting, 25% at panicle initiation, and 25% just before booting. In simulation set II, 150 and 210 kg fertilizer N ha^{-1} were applied either as a single dose at transplanting, three equal splits at transplanting, panicle initiation and booting, or six equal splits in 20-day intervals starting at transplanting. In both sets, variants were included with an indigenous soil N supply of 0.6 and 0.9 kg ha^{-1} d^{-1}, based on parameterization of our field experiments. Both sets were run for 43 years (1961-2003) of weather data from Nanjing, with emergence on May 11 and transplanting on June 15.

Model outputs were used to calculate a number of N use efficiency parameters: partial factor productivity (PFP), physiological efficiency (PE), agronomic efficiency, and fertilizer N recovery (RE):

$$PFP = (Y_0/Nr) + (\Delta Y/\Delta Np) \times (\Delta Np/Nr) \qquad \text{(eqn 4.3)}$$

$$PE = \Delta Y/\Delta Np \qquad \text{(eqn 4.4)}$$

$$AE = \Delta Y/Nr \qquad \text{(eqn 4.5)}$$

$$RE = \Delta Np/Nr \qquad \text{(eqn 4.6)}$$

in which Y_0 is grain yield (kg ha^{-1}) without N inputs, Nr applied N rate (kg ha^{-1}), ΔY incremental increase in grain yield (kg ha^{-1}) that results from N application, and ΔNp the increase in crop N accumulation (kg ha^{-1}) that results from N application.

4.3 Results

4.3.1 Model evaluation

SE and CV values of measured crop variables are given in Table 4.2.

Biomass and leaf area index. Examples of graphical comparison of simulated and measured crop biomass and LAI are given in Fig. 4.1 for the calibration and the validation sets. In general, there was satisfactory agreement between measured and simulated LAI and dry weight of crop organs and of the whole crop. In the calibration set, simulated LAI was slightly overestimated between 80 and 120 days after emergence at 0 and 150 kg N ha^{-1} (Figs. 4.1a, b). In the validation set, LAI was slightly overestimated between 80 and 120 days after emergence at 100 kg N ha^{-1}, but overestimated with 1-2 units from 80 days after emergence onwards at 120 kg N ha^{-1} (Figs. 4.1d, e). Despite these overestimations of LAI, the biomass of crop organs was simulated quite accurately. Goodness-of-fit parameters for the dynamic crop variables are given in Table 4.3. The Student's test indicates that all simulated values were similar to measured values with 95% confidence in both data sets. Slopes (α) of the biomass variables are close to 1 and the intercept (β) values small, indicating a close fit between simulated and measured data. *RMSEa* and *RMSEn* values are 2-3 times higher than the SE and CV values, respectively. Simulation results are less accurate for LAI, with *RMSEa* and *RMSEn* values 3 times higher than the SE and CV of the measured values, respectively.

Table 4.2 Standard error (SE, the same unit as variable) and coefficient of variation (CV, %) for measured crop variables in the field experiments at Nanjing, 2001-2002.

Crop variable	N*	SE	CV
Total biomass (kg ha^{-1})	129	510	7
Biomass of panicle (kg ha^{-1})	50	434	11
Leaf area index (-)	109	0.34	11
Amount of N in crop (kg ha^{-1})	47	14	15
Amount of N in panicle (kg ha^{-1})	21	8	14
Leaf N concentration (g g^{-1})	47	0. 21	8
Yield (kg ha^{-1})	11	947	10

*N is total number of data in experiments I and II.

Crop N-uptake and leaf N concentration. Examples of graphical comparison between simulated and measured crop N uptake and leaf N concentration are given in Fig. 4.2. The error in measured values of crop N variables is larger than those in the crop biomass variables and LAI (Table 4.2). Similarly, the discrepancy between simulated and measured crop N variables is larger than for biomass and LAI, as reflected in higher values for $RMSE_n$ and in values for α and β that deviate more from their ideal values (Table 4.4). Nevertheless, for total crop N uptake and panicle N uptake, *RMSEa* and $RMSE_n$ are only 1.5-2.5 times higher than the SE and CV of the measured values, respectively, in both the calibration and validation data sets. However, for leaf N concentration, $RMSE_a$ and $RMSE_n$ are about 4 times higher than the measured SE and CV values, respectively. In Fig. 4.2, especially the overestimation of leaf N concentration in the first 70 days after emergence is striking. In 2001 of the validation data set, total crop N uptake was overestimated during grain filling, but N uptake in leaves and panicles was simulated accurately.

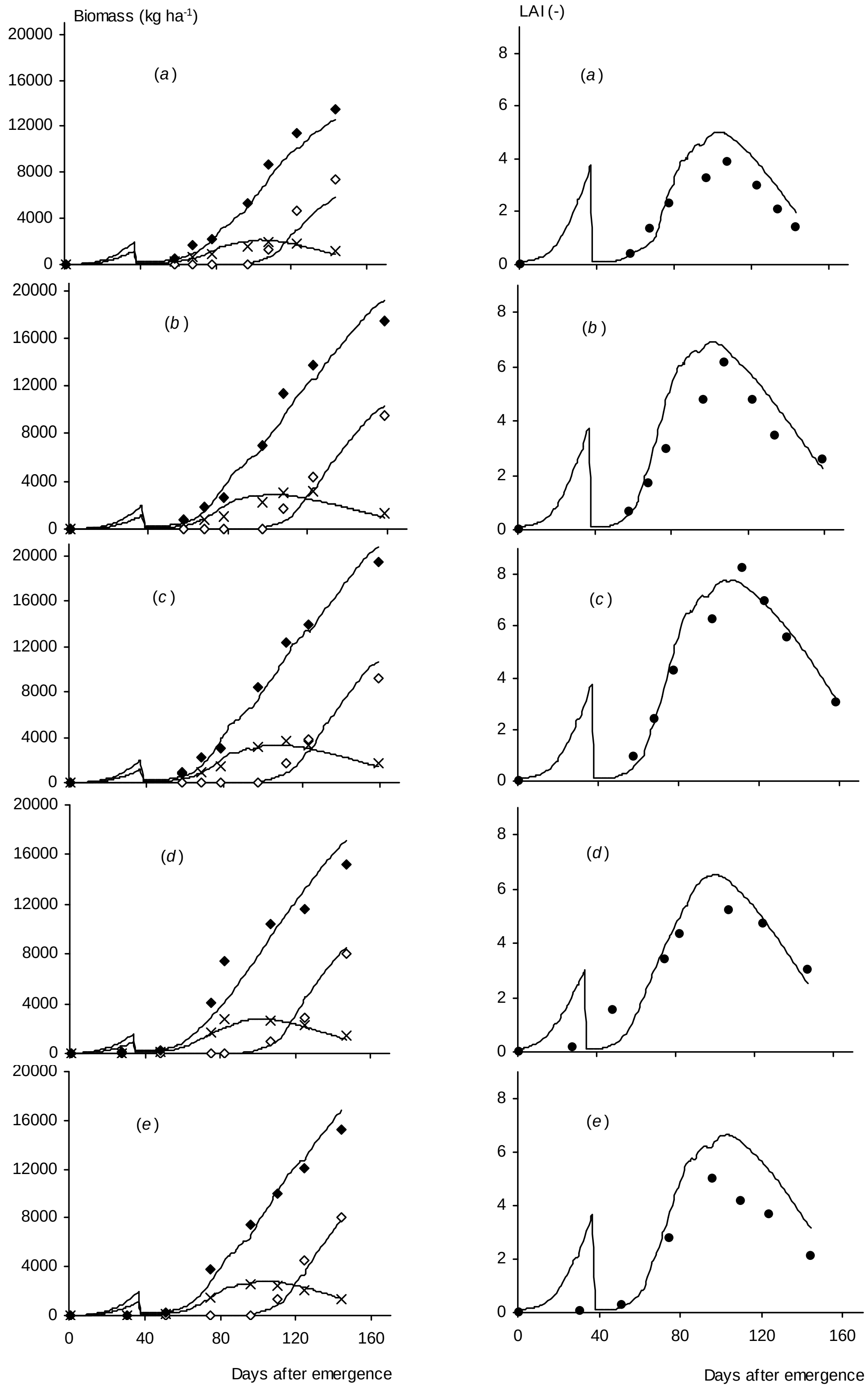


Figure 4.1 Simulated (lines) and measured total aboveground dry matter (♦), leaves (×), panicles (◊), and LAI (●), for experiment I (calibration set) in 2002 (a, b, c) and experiment II (validation set) in 2001 (d) and 2002 (e): (a) 0 kg N ha^{-1}; (b) 150 kg N ha^{-1} with three splits; (c) 300 kg N ha^{-1} in three splits; (d) 100 kg N ha^{-1} in four splits; (e) 120 kg N ha^{-1} in five splits.

Table 4.3 Evaluation results of ORYZA2000 simulations of crop growth variables over the entire growing season, for the calibration and validation data sets.

Crop variable	N	X_{mea} (*SD*)	X_{sim} (*SD*)	*P*(*t*)	α	β	R^2	$RMSE_a$	$RMSE_n$ (%)
Calibration set									
Total biomass (kg ha^{-1})	115	7944 (5664)	7211 (5625)	0.16*	0.971	-500	0.96	1404	18
Biomass of panicles (kg ha^{-1})	44	4233 (3160)	3845 (3333)	0.29*	1.012	-441	0.92	1002	24
Leaf area index (-)	95	4.55 (3.06)	4.51 (2.62)	0.47*	0.807	0.84	0.89	1.26	28
Validation set									
Total biomass (kg ha^{-1})	14	8143 (5194)	8007 (6054)	0.48*	1.139	-1271	0.96	1410	17
Biomass of panicles (kg ha^{-1})	6	4288 (3137)	4437 (3424)	0.47*	1.049	-62	0.92	887	21
Leaf area index (-)	14	3.51 (1.44)	4.34 (1.89)	0.13*	1.210	0.10	0.85	1.12	32

N, number of measured/simulated data pairs; X_{mea}, mean of measured values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of whole population; P(t), significance of paired *t* test; α, slope of linear relation between simulated and measured values; β, intercept of linear relation between simulated and measured values; R^2, adjusted linear correlation coefficient between simulated and measured values; $RMSE_n$ (%), normalized root mean square error between simulated and measured values (%); $RMSE_a$, absolute root mean square error between simulated and measured values.

In a column, * means simulated and measured values are the same at 95% confidence level.

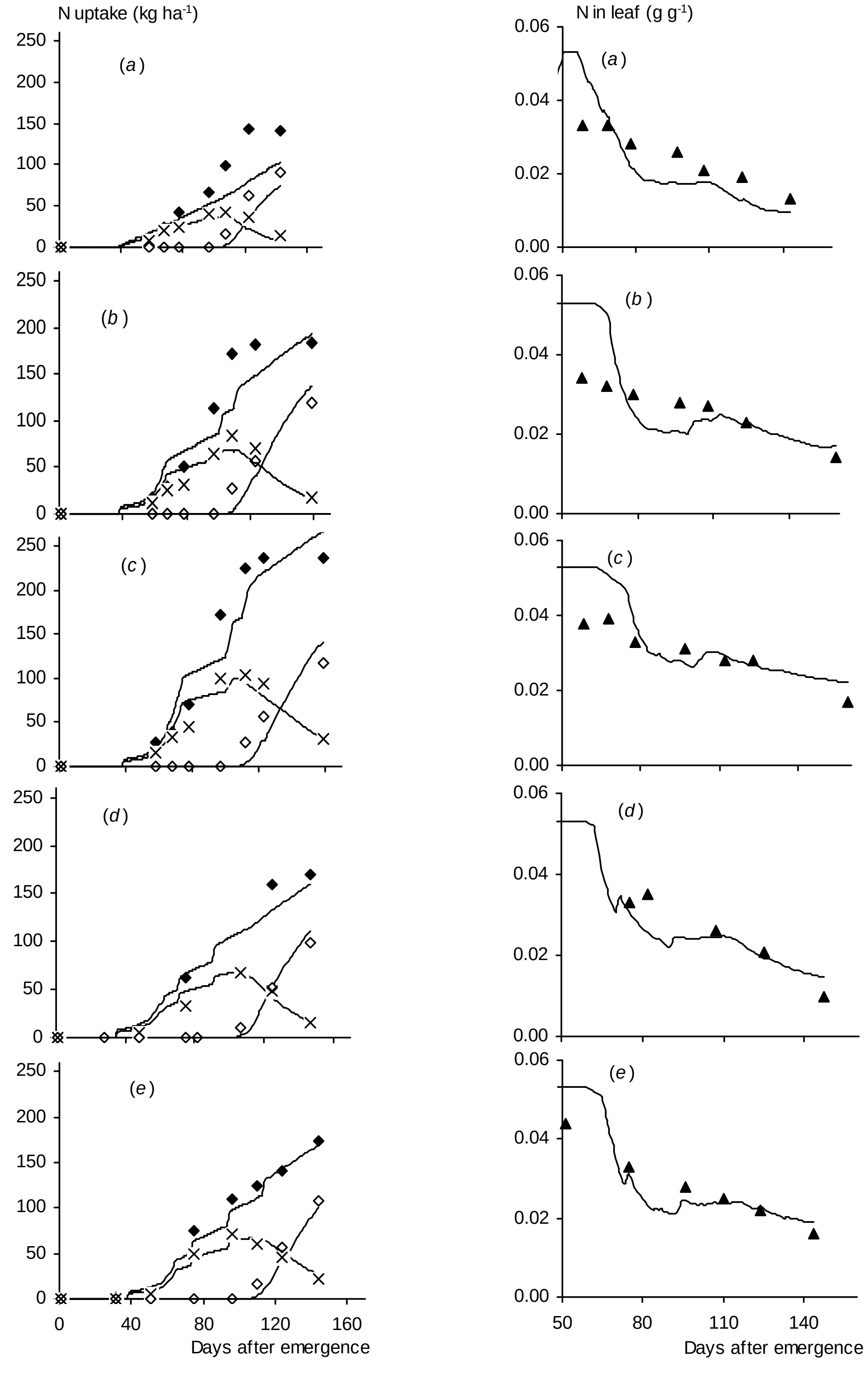


Figure 4.2 *Simulated (lines) and measured total N in crop (♦), leaves (×), and panicles (◊), and N concentration in leaves (▲), for experiment I (calibration set) in 2002 (a, b, c), and experiment II (validation set) in 2001 (d) and 2002 (e): (a) 0 kg N ha^{-1}; (b) 150 kg N ha^{-1} in three splits; (c) 300 kg N ha^{-1} in three splits, (d) 100 kg N ha^{-1} in four splits; (e) 120 kg N ha^{-1} in five splits.*

Table 4.4 Evaluation results of ORYZA2000 simulations of N dynamics in the crop over the entire growing season, for the calibration and validation data sets.

Crop variable	N	X_{mea} (*SD*)	X_{sim} (*SD*)	*P*(*t*)	α	β	R^2	$RMSE_a$	$RMSE_n$ (%)
Calibration set									
Amount of N in crop (kg ha^{-1})	35	107 (76)	97 (66)	0.27*	0.819	9	0.87	30	28
Amount of N in panicles (kg ha^{-1})	15	65 (38)	53 (54)	0.25*	1.410	-38	0.96	20	30
N concentration in leaves (g g^{-1})	35	0.028 (0.007)	0.029 (0.014)	0.23*	1.552	-0.013	0.67	0.009	33
Validation set									
Amount of N in crop (kg ha^{-1})	12	104 (66)	89 (56)	0.26*	0.794	6	0.85	29	28
Amount of N in panicles (kg ha^{-1})	6	57 (40)	52 (47)	0.41*	1.141	-14	0.96	12	20
N concentration in leaves (g g^{-1})	12	0.030 (0.011)	0.028 (0.011)	0.30*	0.761	0.005	0.54	0.008	27

N, number of measured/simulated data pairs; X_{mea}, mean of measured values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of whole population; P(t), significance of paired *t* test; α, slope of linear relation between simulated and measured values; β, intercept of linear relation between simulated and measured values; R^2, adjusted linear correlation coefficient between simulated and measured values; $RMSE_n$ (%), normalized root mean square error between simulated and measured values (%); $RMSE_a$, absolute root mean square error between simulated and measured values.

In a column, * means simulated and measured values are the same at 95% confidence level.

Another way to compare simulated and measured crop N variables is the so-called “three-quadrant diagram” (De Wit, 1953; Van Keulen, 1982; Fig. 4.3). Three-quadrant diagrams show the relationships between N application rate and yield (quadrant I), total N uptake and yield (quadrant II), and N application rate and total N uptake (quadrant III). In all quadrants, simulated and measured values of yield and crop N uptake fall on the same curve. In quadrant II, crop N uptake is underestimated in the low uptake range in the 0-N plots, while it is overestimated in the high uptake range. Seasonal-average fertilizer N recovery, calculated from the slope of the curve in quadrant III, is 40%.

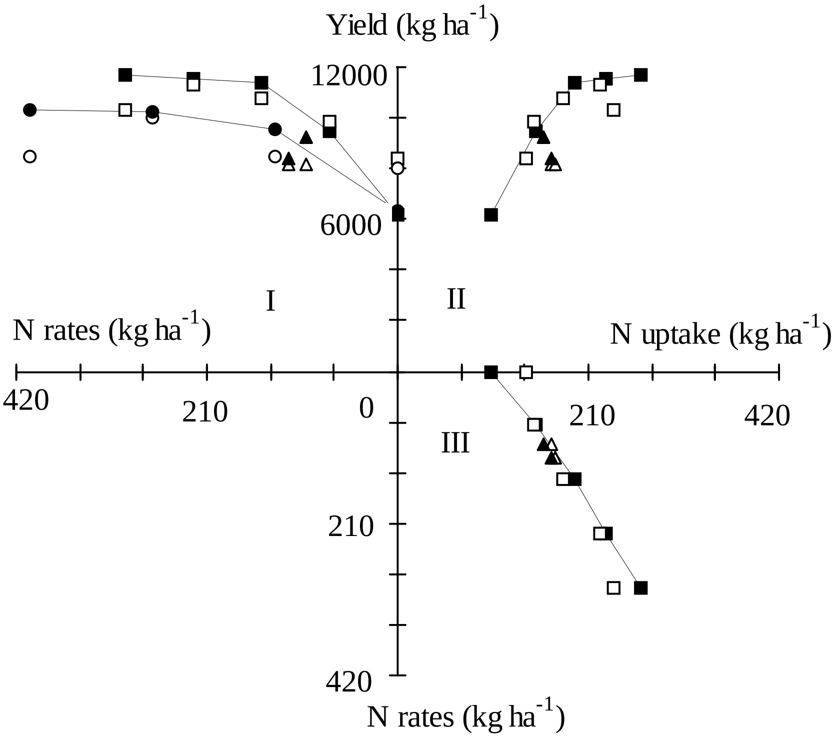


Figure 4.3 Three-quadrant diagram of measured (for SE see Table 4.2) and simulated yield, N uptake, and applied fertilizer N. Simulated (●) and measured (○) values for experiment I with 0, 135, 270, 405 kg N ha^{-1} in 2001; simulated (■) and measured (□) values for experiment I with 0, 75, 150, 225, 300 kg N ha^{-1} in 2002; simulated (▲) and measured (△) values for experiment II in both 2001 and 2002.

Final biomass and yield. Simulated and measured values of total crop biomass and grain yield at harvest are given in Fig. 4.4 for both the calibration and the validation data sets. Because of the low number of data, the goodness-of-fit parameters were calculated for both data sets combined (Table 4.5). In general, simulated and measured values match quite well. In Fig. 4.4, most data points are near the 1:1 line and within the +/-SE lines of measured values. For yield, $RMSE_a$ and $RMSE_n$ are of the same order of magnitude as the SE and CV values, respectively.

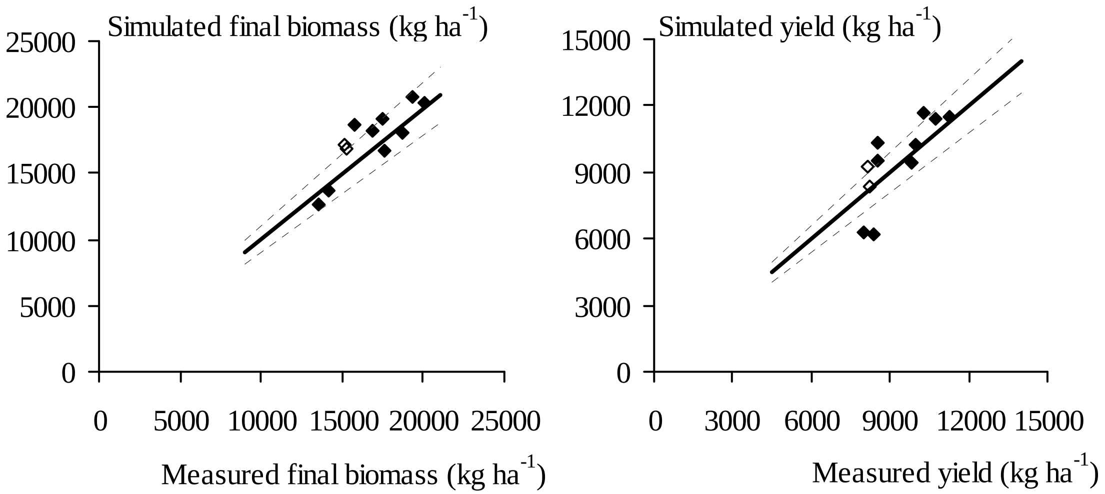


Figure 4.4 Simulated versus measured end-of season total biomass and yield. Data for experiment I (♦) and experiment II (◊). Solid lines are the 1:1 relationships; dotted lines are plus and minus mean standard error of measured values around the 1:1 line.

Table 4.5 Evaluation results of ORYZA2000 simulations of final biomass and grain yield, for the combined calibration and validation data sets.

Crop variable	N	X_{mea} (*SD)*	X_{sim} (*SD)*	*P*(*t*)	α	β	R^2	RMSE$_a$	RMSE$_n$ (%)
Final biomass (kg ha^{-1})	11	16723 (2144)	17472 (2514)	0.23*	0.987	958	0.71	1417	8
Yield (kg ha^{-1})	11	9263 (1189)	9478 (1897)	0.38*	1.237	-1983	0.60	1193	13

N, number of measured/simulated data pairs; X_{mea}, mean of measured values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of whole population; P(t), significance of paired *t* test; α, slope of linear relation between simulated and measured values; β, intercept of linear relation between simulated and measured values; R^2, adjusted linear correlation coefficient between simulated and measured values; RMSE$_n$ (%), normalized root mean square error between simulated and measured values (%); RMSE$_a$, absolute root mean square error between simulated and measured values.

In a column, * means simulated and measured values are the same at 95% confidence level.

4.3.2 Scenario analysis

Simulation set I. Fig. 4.5 gives the simulated yields for the 43 years of simulation at four combinations of low (0 N) and high (300 kg N ha^{-1}) fertilizer N rate and low (0.6 kg ha^{-1} d^{-1}) and high (0.9 kg ha^{-1} d^{-1}) indigenous soil N supply. The differences in simulated yields among the years are a consequence of differences in solar radiation and temperature only. At high rates of N application, the differences among the years are relatively large: at 300 kg N ha^{-1}, yield fluctuates between about 9,000 and 13,000 kg ha^{-1}, with four years exceeding 14,000 kg ha^{-1}. At lower N application rates, yields are lower and yield differences among the years smaller: at 0 kg fertilizer N ha^{-1} and an indigenous soil N supply of 0.6 kg ha^{-1} d^{-1}, yield fluctuates between about 5,000 and 6,000 kg ha^{-1}. At low fertilizer levels, the effect of indigenous soil N supply is relatively large whereas at high fertilizer N levels it is negligible. Overall, a high availability of N is required to realize the climatic yield potential under favourable weather conditions.

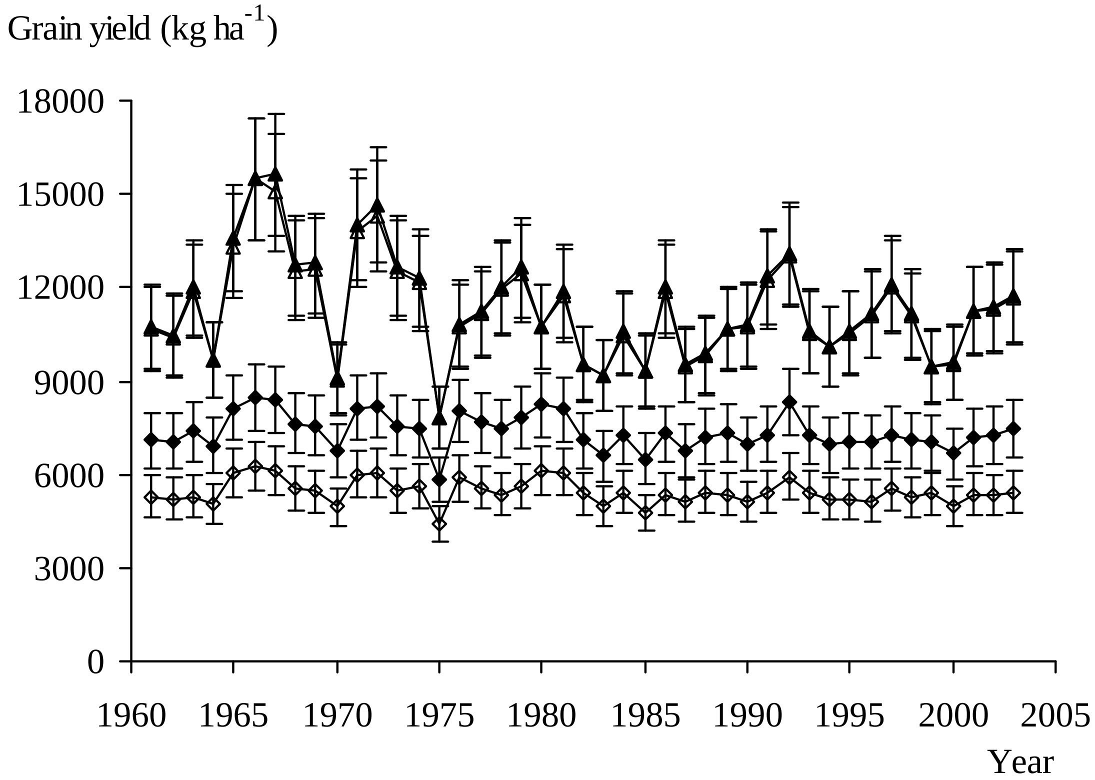


Figure 4.5 Simulated yields between 1961 and 2003, with indigenous soil N supply of 0.6 kg ha^{-1} d^{-1} and fertilizer N rates of 0 (◊) and 300 kg ha^{-1} (Δ), and with indigenous soil N supply of 0.9 kg ha^{-1} d^{-1} and fertilizer N rates of 0 (♦) and 300 kg ha^{-1} (▲). The bars indicate the normalized root mean square error of simulated versus measured yield.

Fig. 4.6 presents the results of the simulations in the three-quadrant diagram, using values averaged over the 43 years of simulation. Differences in indigenous soil N supply result in different fertilizer N response curves (quadrant I), starting at different yields with 0 fertilizer N (at low indigenous soil N supply, yield is 65% of that at high indigenous soil N supply), but converging at a yield level of about 10-11,000 kg ha^{-1} at around 200 kg fertilizer N ha^{-1}. At low indigenous soil N supply, some 60 kg fertilizer N ha^{-1} is needed to realize the 0-N yield (close to 6,000 kg ha^{-1}) at high indigenous soil N supply. Agronomic efficiency, the slope of the curve between yield and N application rate in quadrant I, is highest at zero fertilizer N application and decreases to 0 at application rates exceeding about 300 kg ha^{-1}. Moreover, agronomic efficiency decreases with increasing indigenous soil N supply, from 35 kg kg^{-1} at 0 kg fertilizer N ha^{-1} and low indigenous soil N supply to 30 kg kg^{-1} with high indigenous soil N supply.

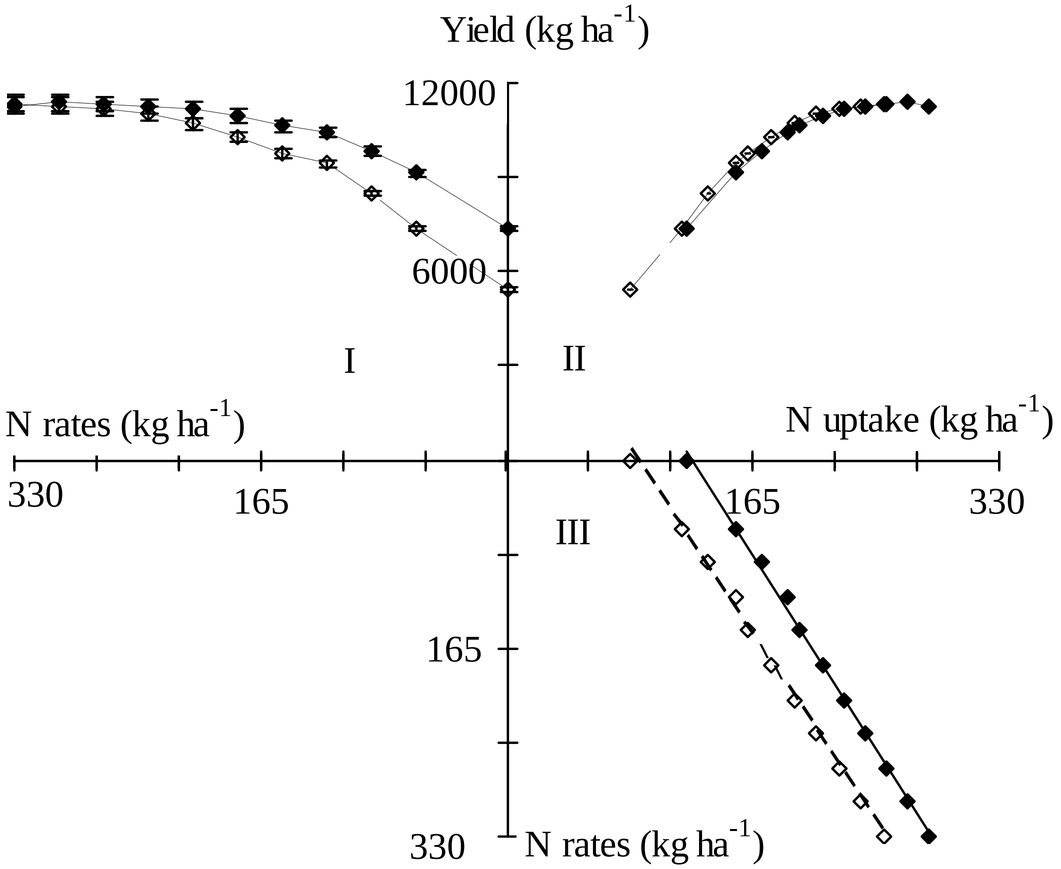


Figure 4.6 Three-quadrant diagram of simulated yield, N uptake, and applied fertilizer N, with indigenous soil N supply of 0.6 kg ha^{-1} d^{-1} (◊) and 0.9 kg ha^{-1} d^{-1} (♦). Each simulation is the average of 43 years between 1961 and 2003.

The relation between grain yield and N uptake (quadrant II) is identical for low and high indigenous soil N supply. At low fertilizer rates, yield increases linearly with N uptake at a physiological efficiency (the slope of the curve between yield and N uptake) of 54 kg kg^{-1}. At fertilizer rates exceeding 150 kg N ha^{-1}, the curve levels off and reaches a plateau at about 225 kg fertilizer N ha^{-1}, where radiation or temperature limit yield. Over the range of fertilizer N rates studied in this scenario, N uptake by the crop increases linearly with fertilizer N rates (quadrant III), at both low and high indigenous soil N supply. Seasonal-average fertilizer N recovery is 54% at low and 51% at high indigenous soil N supply.

Simulation set II. The timing and number of splits in fertilizer N application has small effects on yield, that are significant only at low indigenous soil N supply (Table 4.6). Lowest yields were associated with either 100% basal dressing at transplanting, or with complete omission of fertilizer N at transplanting. The treatments with 100% basal application combine the highest physiological efficiencies with the lowest agronomic efficiencies and fertilizer recoveries. Omitting fertilizer application at transplanting, and applying it in two equal splits at panicle initiation and at booting, results in the highest crop N uptake and fertilizer recovery, but in low agronomic and physiological efficiencies. At 210 kg fertilizer N ha^{-1}, this treatment has the lowest yields of all splits. At both fertilizer levels and indigenous soil N supplies, the highest yield, partial factor productivity and agronomic efficiency are realized with splitting the amount of fertilizer N equally at transplanting, panicle initiation and booting. However, this treatment has intermediate levels of fertilizer N recovery. Increasing the number of splits to six does not further increase yield or any of the N use efficiency parameters.

Table 4.6 Means of simulated grain yield, N uptake and N use efficiency parameters at different N rates, splits and indigenous soil N supply rates, using 43 years historical weather data from 1961 to 2003.

Indigenous soil N supply rate (kg ha^{-1}d^{-1})	Fertilizer N rate (kg ha^{-1})	Fertilizer N splits (kg ha^{-1})	Grain yield (kg ha^{-1})	Total N uptake (kg ha^{-1})	PFP (kg kg^{-1})	Y_0/Nr (kg kg^{-1})	PE (kg kg^{-1})	RE (%)	AE (kg kg^{-1})
0.6	150	150	9092	146	61	36	58	42	24
		0, 75, 75	9476	178	63	36	43	63	27
		50, 20, 20, 20, 20, 20	9622	163	64	36	52	53	28
		50, 50, 50	9753	167	65	36	51	56	29
		LSD	*166*	*2*					
	210	210	10266	172	49	26	54	42	23
		0, 105, 105	9803	212	47	26	34	62	21
		70, 28, 28, 28, 28, 28	10598	195	50	26	46	53	25
		70, 70, 70	10769	199	51	26	46	55	28
		LSD	*221*	*3*					
0.9	150	150	10339	182	69	49	49	40	20
		0, 75, 75	10411	213	69	49	33	61	20
		50, 20, 20, 20, 20, 20	10531	198	70	49	41	51	21
		50, 50, 50	10681	201	71	49	42	53	22
		LSD	*218*	*2*					
	210	210	10984	207	52	35	42	41	17
		0, 105, 105	10631	245	51	35	26	59	16
		70, 28, 28, 28, 28, 28	11077	228	53	35	35	51	18
		70, 70, 70	11115	232	53	35	34	53	20
		LSD	*259*	*3*					

The fertilizer splits are applied at transplanting for one split, at transplanting, panicle initiation and booting for three splits, transplanting and at intervals of 20 days after transplanting for six splits. LSD is least significant difference between fertilizer N treatments. PFP is partial factor productivity for applied N; Y_0 is grain yield at 0 kg N ha^{-1}; Nr is the amount of applied fertilizer N; PE is physiological N efficiency; RE is fertilizer N recovery; AE is agronomic N efficiency.

4.4 Discussion and conclusions

There are no absolute criteria to classify a model as “good” or “bad”. Strictly speaking, models can not be validated; only invalidation is possible on the basis of empirical evidence. However, repeated and well-documented comparisons between model simulations and experimental measurements increase the confidence in the suitability of a model for a specific purpose (Bouman and Van Laar, 2006). For our purpose, and from our evaluation, we conclude that ORYZA2000 satisfactorily reproduced measured crop variables in both the calibration and the validation experimental data set. For yield, LAI and crop biomass, the goodness-of-fit parameters (slope, intercept, and coefficient of determination of the linear regression between simulated and measured values, and the root mean square errors between simulated and measured values) and the graphical analyses of the results of the simulation for the japonica variety Wuxiangjing9, used in our experiments, were comparable to those for the tropical high-yielding variety IR72 in the Philippines (Bouman and Van Laar, 2006). For yield, the root mean square error between simulated and measured values was of the same order of magnitude as the coefficients of variation of measured values. The simulated crop N variables, such as leaf N concentration and crop N uptake were slightly less accurate than those of crop biomass, LAI and yield. Simulation accuracies might be increased by improving the simulation of soil N dynamics, which in ORYZA2000 is relatively simple. Total N availability is determined by a constant indigenous soil N supply rate and a maximum recovery of applied fertilizer N, defined as a function of crop development stage (Bouman *et al.*, 2001). In reality, indigenous soil N supply rate can vary substantially in the course of the growing season (Dobermann *et al.*, 2003a, b; Thiyagarajan *et al.*, 1997). The recovery of fertilizer N depends not only on crop development, but also on management (*e.g.*, depth of placement, fertilizer type) and environmental conditions that affect volatilization and leaching losses. More detailed modelling of soil N transformations and losses may increase the accuracy of simulating soil N dynamics and crop N uptake, but requires detailed soil information (Godwin and Jones, 1991; Godwin and Singh, 1998; Van Keulen, 2001).

The simulated high yields of 9-13,000 kg ha^{-1} at high fertilizer N rates are supported by the high yields in our field experiments (up to 11,500 kg ha^{-1} at 225 kg N ha^{-1}, Fig. 4.2). These high yields are associated with the long crop duration of about five months. The very high simulated yields of 14-15,000 kg ha^{-1} require confirmation through well-designed field experiments under conditions of potential production and favourable weather conditions. Supporting evidence for the feasibility of such high yields has been reported for Yunnan, China, and Southeast Australia, where crop growth durations are about five to six months and radiation levels relatively high (Horie, 2001; Horie *et al*., 2004).

The indigenous soil N supply rates of 0.6 and 0.9 kg ha^{-1} d^{-1} found in our experiments compare well with values of 0.5-0.9 kg reported for tropical rice soils by Ten Berge *et al*. (1997), and with values up to 1 kg ha^{-1} d^{-1} reported by Dobermann *et al*. (2003a, b) for Southeast China. Both, the field experiments and the model explorations show that the marginal yield increase at fertilizer N rates above 200 kg ha^{-1} is very low (Figs. 4.3 and 4.6). Current fertilizer N rates in irrigated rice production in Southeast China are 260-300 kg ha^{-1}, with yields of summer rice of 6-8,000 kg ha^{-1} (Cui *et al*., 2000; Peng *et al*., 2002; Wang *et al*., 2001; Witt *et al*., 1999). Our simulation results suggest that there still is scope for some 2-3,000 kg ha^{-1} yield increase, while using less fertilizer N of around 200 kg ha^{-1} at 0.6-0.9 kg ha^{-1} d^{-1} indigenous soil N supply rates (Fig. 4.6, quadrant I).

Fertilizer N use efficiency can generally be increased by matching N-supply as close as possible with crop demand. Common practice in China is to apply all fertilizer N in one or two splits within the first 10 days after transplanting, and it has been suggested that fertilizer N use efficiency could be improved by increasing the number of splits and by later applications (Cabangon *et al*., 2004; Wang *et al*., 2001). Ten Berge *et al*. (1997) recommended frequent, small doses of fertilizer on the basis of optimization. However, with increasing urbanization and the movement of labour out of agriculture, farm operations need to be minimized. A labour-efficient strategy is to apply fertilizers in a limited number of applications at the time when the crop needs it most. In our experiments and simulations, crop N uptake generally peaked between maximum tillering and panicle initiation (Fig. 4.2). The contribution of N acquired at this stage to grain yield formation is relatively large (Cassman *et al*., 1996; Peng *et al*., 1996). Thiyagarajan *et al*. (1997) suggested that part of the basal fertilizer N in irrigated rice could be delayed to this growth stage to increase N use efficiency. In field experiments with summer rice in Tuanlin, Hubei province, and in Jinhua, Zhejiang province, Belder *et al*. (2005) and Cabangon *et al*. (2004) found that increasing the number of splits from two (50% one day before transplanting and 50% 10 days after transplanting) to four, resulted in higher fertilizer N recovery, total N uptake and agronomic N use efficiency, but hardly affected grain yield. In two out of three years, the fertilizer N recovery (41-72%), physiological N use efficiency (45-68 kg kg^{-1}) and agronomic N use efficiency (15-24 kg kg^{-1}) in their well-watered treatments are in the same range as found in our simulation study (Table 4.6), confirming the feasibility of high N use efficiencies in irrigated rice. Our simulation results also show that manipulating the number of fertilizer N splits had only small effects on grain yield. Within the narrow variation in yield (10% around the mean), concentrating fertilizer N at transplanting resulted in lower yields, lower fertilizer N recoveries and lower agronomic N use efficiencies. On the other hand, omitting N application at transplanting completely, and applying N in two splits in the period of high demand, introduces a risk of lower yields than with other splits. Highest yield, partial N productivity and agronomic N use efficiency, and second-highest fertilizer N recovery, were obtained with three equal doses at transplanting, panicle initiation and booting. Increasing the number of splits to six had no effects.

Other approaches to improve N use efficiency are the use of organic forms of N, controlled-release N fertilizer (Shoji and Kanno, 1994), or incorporation of the fertilizer into the soil (Schnier *et al.*, 1990). These practices, however, entail higher costs or labour requirements than split application of conventional fertilizers (Buresh and Baanante, 1993).

5 Quantifying N response and N use efficiency in Rice-Wheat (RW) cropping systems under different water management

Q. Jing[1,2,3], H. van Keulen[2,3], H. Hengsdijk[2], W. Cao[1], P.S. Bindraban[2], T. Dai[1], D. Jiang[1]

[1] Key Lab of Crop Growth Regulation, Ministry of Agriculture, Nanjing Agricultural University, Nanjing 210095, China
[2] Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA Wageningen, the Netherlands
[3] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, the Netherlands

Abstract

About 10% of the food supply in China is produced in Rice-Wheat (RW) cropping systems. Over the last decades, nitrogen (N) input associated with intensification has increased much stronger than N output in these systems. The resulting nitrogen surplus increases the risk of environmental pollution and the economic costs of production. We studied the effects of N and water management on yields of rice and wheat, and nitrogen use efficiencies in RW systems. A RW-field experiment with nitrogen rates from 0 to 300 kg N ha^{-1} with continuously flooded and intermittently irrigated rice crops was carried out at Jiangpu experimental station of Nanjing Agricultural University of China (32° 4′ N, 118° 48′ E) from 2002 to 2004 to identify improved nitrogen management practices in terms of productivity and nitrogen use efficiency.

Results show that nitrogen uptake by both rice and wheat increased with higher N rates, while agronomic nitrogen use efficiency (kg grain per kg N applied) declined at rates exceeding 150 N kg ha^{-1}. Highest combined grain yields of rice and wheat were obtained at about 150 and 300 kg N ha^{-1} season^{-1} in rice and wheat, respectively. Carry-over of residual N from rice to the subsequent wheat crop was limited, consistent with low soil nitrate contents after rice harvest. Total soil N content hardly changed during the experiment, while soil nitrate contents were much lower after wheat than after rice harvest. There were no significant effects of water management on yield and N uptake by rice, but apparent N recovery was higher under intermittent irrigation. In one season, intermittent irrigation management in rice resulted in higher N uptake in the subsequent wheat season, but not in higher yield. Uptake of indigenous soil N was much higher in rice than in wheat, while in rice it was much higher than values reported in literature, which may have consequences for nitrogen recommendations based on indigenous N supply.

Keywords: apparent N recovery, N balance, soil nutrients, system analysis.

5.1 Introduction

In China, as in many other parts of Asia, rice and wheat are frequently grown in rotation. Rice-wheat (RW) systems occupy 10% of the arable area in China, mainly along the Yangtze River (Huke and Huke, 1992). These systems are of major importance for achieving China's food security. The population of China is expected to increase with nearly half a billion people by 2030 (FAO, 2003), requiring large quantities of rice and wheat. Since suitable agricultural land is scarce in China, RW systems are very intensively managed, *i.e.* with high inputs to maximize yields per unit of land. Particularly in Southern Jiangsu Province, extremely high annual doses of 500-650 kg N ha^{-1} are common in RW systems (Zhu *et al*., 2000), with low nitrogen use efficiency (Cui *et al*., 2000; Peng *et al*., 2002; Xu and Wu, 1999). Increasing N inputs beyond crop needs results in undesired emissions to the environment, such as gaseous and leaching losses and runoff to surface water and in unnecessary production costs for farmers (Li and Zhang, 1999; Xing and Zhu, 2000).

Commonly, the rice crop in RW systems is grown by keeping a permanent layer of water on the field, resulting in higher seepage and percolation losses than in the wheat crop. Competing claims for fresh water sources call for more efficient use of irrigation water in rice production (Bouman and Tuong, 2001). To reduce water use in irrigated rice production, water-saving techniques are being developed. Such techniques include the introduction of periods with saturated but non-flooded soil conditions during part of the growing period also known as intermittent irrigation (Mao, 1993), direct seeding of rice under non-flooded conditions (Xie *et al*., 1995), and the introduction of ground cover, reducing evaporation losses (Lin *et al*., 2002). Intermittent irrigation has been shown to lead to reduced water input in rice systems without affecting yields (Belder *et al*., 2004, 2005). Water-saving techniques in rice may improve soil physical and biological properties for the associated wheat (Timsina and Connor, 2001), resulting in increased N use efficiencies in the wheat crop (Zheng, 2000).

There has been much research on N dynamics in rice and wheat separately, but only few studies have reported on N dynamics in RW-systems (Timsina *et al*., 2001).

Especially information on N dynamics in RW-systems in relation to intermittent irrigation is scarce, which hampers development of RW-systems aiming at more efficient use of water and nitrogen. This study aims at analysing N response and N use efficiency in a rice-wheat system on the basis of a two-year field experiment with two seasons of rice and wheat, different nitrogen regimes, and different water management in the rice crop, including conventional flooding and intermittent irrigation. Grain yield and N uptake of crops under different treatments were compared, and soil nutrients were monitored, including total N content and nitrate content. Apparent N recovery, agronomic and physiological N use efficiency of single crops are analysed, using the three-quadrant method (De Wit, 1953; Van Keulen, 1982) to explore opportunities for improvements in N use efficiency in RW cropping systems.

5.2 Material and methods

5.2.1 Experimental design

The experiments were carried out at Jiangpu experimental station of Nanjing Agricultural University at Nanjing (32°4′ N, 118°48′ E) from 2002 to 2004, covering two sequences of rice and wheat crops. The soil belongs to the Anthrosols with pH 7.1, available phosphorus 23.9 mg kg^{-1} and available potassium 95.7 mg kg^{-1}. Japonica rice cultivar Wuxiangjing9 and wheat cultivar Yangmai10 were used.

5.2.2 Management and treatments in the rice season

The experiment was a two-factor split plot design. The main-factor, water management consisted of two treatments, *i.e.* conventional irrigation (CI) and intermittent irrigation (II). The sub-factor nitrogen management consisted of five application rates, *i.e.* 0, 75, 150, 225 and 300 kg ha^{-1}. Plot size was 10 × 3 m^2 with three replications for each treatment. Plots were separated by plastic film to 30 cm below soil surface to reduce water and nitrogen flows between adjacent plots. In 2002, rice was sown on May 11 and transplanted as six–leaf seedlings on June 15 at one seedling per hill, spaced at 25 and 15 cm between and in the rows, respectively. Because of differences in maturity, the 0 kg N ha^{-1} plots were harvested on October 5, the remaining II-plots on October 15 and the remaining CI-plots on October 21. After transplanting, the CI treatment was flooded with a water layer of 2 to 5 cm, except during mid-season drainage for two days, starting on July 31 and for five days starting on August 25 in 2002. Soil water content in II was maintained throughout the growth period between about 85% relative water content (when the soil started to form cracks) and saturation, through drainage or irrigation. Before transplanting, 60% of the total nitrogen was applied as basal fertilizer, another 20% at 15 days after jointing, and the remaining 20% at 25 days after jointing (5 to 10 days before heading). In addition to nitrogen, 135 kg P_2O_5 and 210 kg K_2O ha^{-1} was applied as basal fertilizer.

In 2003, rice was sown on May 15 and transplanted June 15 in a 30×15 cm pattern. On October 23, all plots were harvested. Crop management was identical to that in 2002.

5.2.3 Management and treatments in the wheat season

In 2002, after the rice harvest, the land was ploughed and seed was drilled on November 9 at 180 grains per m^2. Each rice plot was sub-divided into three to apply three N rates to wheat, *i.e.* 0, 150 and 300 kg ha^{-1}. Before sowing, 60% of the N was applied and the remainder was top-dressed at the jointing stage. In addition, 135 kg P_2O_5 and 210 kg K_2O ha^{-1} was applied as basal fertilizer. Wheat was harvested on June 3.

In 2003, an alternative lay-out was selected, based on the results of the previous year: the rice plots were split in two, with half receiving the same N-doses as in the rice season, while the other half did not receive any N. Before sowing of the wheat crop, the soil was prepared with a rotating plough and 60% of the fertilizer was applied, the remainder being applied in equal splits at jointing and booting. All plots received 135 kg P_2O_5 and 210 kg K_2O ha^{-1} as basal fertilizer. Wheat was sown on November 6 at a density of 150 grains per m^2 and was harvested on May 26.

5.3 Measurements

5.3.1 Dry weight and nitrogen content

During the entire experiment, dates of key growth stages of crops were recorded. Both, rice and wheat plants of 1 m^2 from each plot were harvested to determine panicle/spike number, grain number per panicle/spike and 1000-grain weight. The filled grain percentage was determined from the number of filled grains per panicle, filled grains were selected in a NaCl solution with a specific gravity of 1.03. Plant samples, separated in grain and straw were oven-dried at 80 ^{o}C for 2 days. The yields are measured from the samples and showed on the basis of moisture content of 14% for both wheat and rice. Concentrations of N in grain and straw were determined by micro-Kjeldahl (AOAC, 1984), following digestion in a H_2SO_4–H_2O_2 solution.

5.3.2 Soil nitrogen

Total and nitrate nitrogen content in the 0-40 and 40-80 cm soil layers were periodically monitored, both before and after crop growth in the plots of 0, 150 and 300 kg N ha^{-1} under both water management treatments. Nitrate (NO_3-N) was extracted from fresh soil samples using an equilibrium extraction with 2.0 N KCl solution and analysed using a flow analyzer. Total soil N content was determined after air-drying of soil samples, using micro-Kjeldahl, following digestion in a H_2SO_4–H_2O_2 solution.

5.3.3 Nitrogen use efficiency indicators and analysis

Apparent nitrogen recovery (ANR, %) is the ratio of the difference in N uptake between the treated and the zero-fertilizer plot to the application rate. Physiological N use efficiency (NUE, in kg grain dry matter per kg N) is defined as grain production per unit N uptake by the crop, while agronomic efficiency (AE, in kg grain dry matter per kg N) is defined as grain production per unit N applied. These characteristics are presented in three-quadrant graphs (De Wit, 1953; Van Keulen, 1982): One quadrant presents grain yield against N application (fertilizer response curve, AE), the second, yield against N uptake (yield-uptake curve, NUE), and the third relates N application to N uptake (application-uptake curve, ANR). Only two out of these three relations are mutually independent: the third relation always follows from the two others.

5.3.4 Weather data

Daily weather data, *i.e.* radiation, precipitation, maximum and minimum temperatures were collected from a nearby meteorological station.

5.4 Results

5.4.1 Weather

Average daily solar radiation during the first rice growing season was 14.94 MJ m^{-2} compared to 13.15 MJ m^{-2} during the second season (Fig. 5.1). Rainfall in the second rice season was more frequent and much higher than in the first rice season (1054 *vs*. 421 mm). Average temperature was 25.7 °C in the first *vs*. 25.1 °C in the second season. Frequency of rainfall in the first wheat season was higher than in the second, although total rainfall was more or less similar (511 *vs*. 435 mm). However, the higher rainfall frequency and associated cloudiness resulted in an average daily solar radiation during the first wheat season of 12.95 MJ m^{-2} compared to 14.35 MJ m^{-2} during the second season. Consistent with the higher radiation, average temperature during the second wheat season was 11.4 °C *vs*. 10.1 °C in the first season.

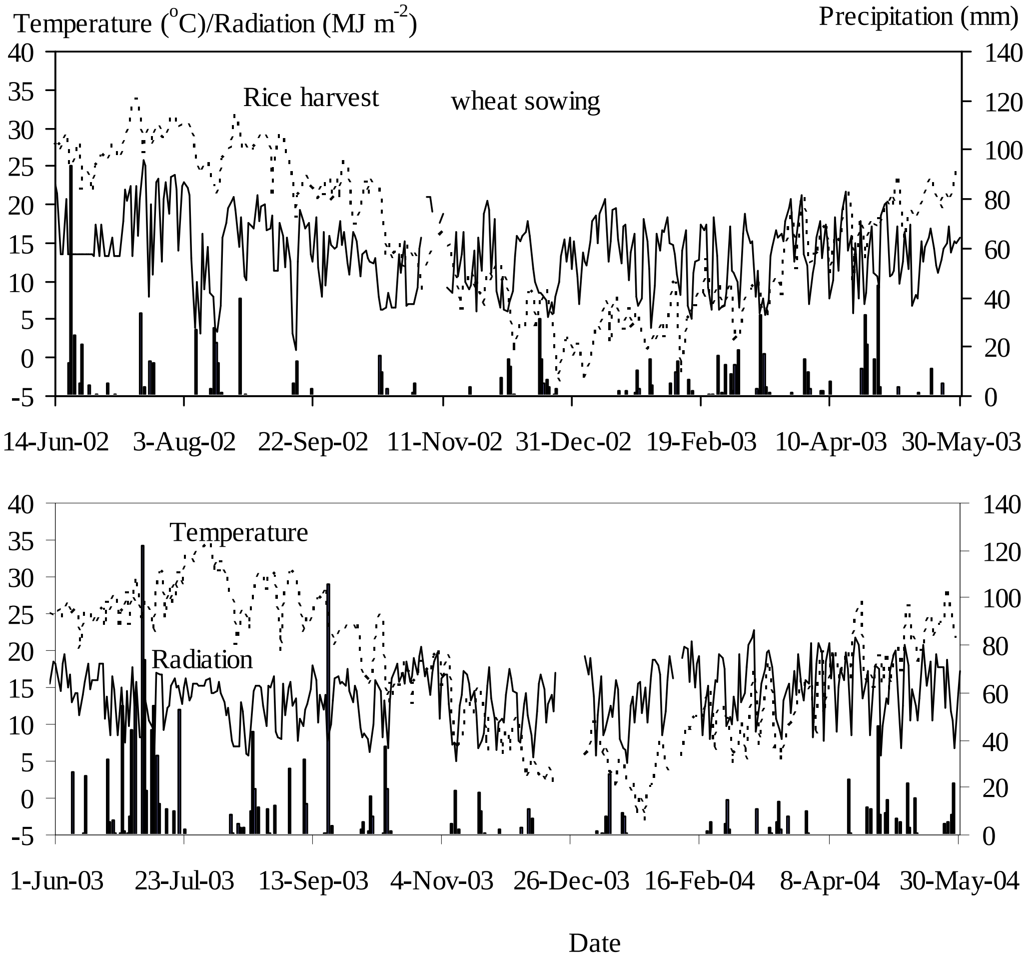


Figure 5.1 Daily mean temperature, radiation and precipitation at Nanjing in two seasons of rice-wheat rotations. Solid lines are radiation, dotted lines are temperature, and columns are precipitation.

5.4.2 Rice

Grain yield

In both seasons, effects of nitrogen rates on yields were statistically significant, but water management treatments were not different (Table 5.1). There was no interaction effect of water and nitrogen on yield, hence N fertilizer response for the two irrigation methods was similar. Grain yield first increased with increasing N rates, and started to decrease at N rates of 225 kg ha^{-1}. The lower yields at the highest N rates were generally associated with lower percentages of filled grains. At low N rates, spikelet numbers per unit area were lowest. Spikelet number per m^2 was significantly higher in the first year (42,800) than in the second year (34,000), as was grain yield, *i.e.* 9.6 Mg ha^{-1} in the first *vs*. 8.0 in the second year. There was no interaction effect between years and treatments, indicating consistent yield responses with respect to N and water management in both years.

Table 5.1 Average (two seasons, 2002 and 2003) yield components, grain yield and N uptake in aboveground material at maturity of rice at different N rates and for two irrigation methods, and their variation source.

Treatment	Spikelet no. (10^3 m^{-2})	1000-grain weight (g)	Filled grains (%)	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})
Irrigation (I)					
CI	39.7	24.3	68	8956	171
II	37.1	24.4	69	8713	173
$LSD_{0.05}$	*6.8*	*0.29*	*7*	*606*	*16*
N rate (kg ha^{-1})					
0	27.0	24.4	74	6925	111
75	33.9	24.3	75	8468	150
150	39.6	25.0	70	9730	176
225	46.5	24.1	63	9880	207
300	45.0	24.0	61	9169	214
$LSD_{0.05}$	*8.3*	*0.45*	*11.5*	*959*	*26*
Year					
2002	42.8	24.4	63	9597	194
2003	34.0	24.3	75	8072	149
$LSD_{0.05}$	*4.5*	*0.30*	*4*	*405*	*22*
Variation source					
Y×I	NS	NS	NS	NS	NS
Y×N	**	NS	**	NS	NS
I×N	NS	*	NS	NS	NS

*,** significant at 0.05 and 0.01 probability levels; NS not significant.

Aboveground N uptake

N uptake in the aboveground parts of rice was not significantly different between both water management treatments (Table 5.1), but increased significantly with increasing N rates. Below 150 kg N ha^{-1}, total N removed in the crop exceeded N fertilizer input, while at the higher rates it was reversed. There was no interaction effect between N and water management on N uptake. Consistent with the yield difference between both years, crop N uptake in 2002 was clearly higher than in 2003 (194 *vs*. 149 kg ha^{-1}), associated with N uptake in the control (0 kg N ha^{-1}) plots, *i.e.* 130 kg ha^{-1} in 2002 and 91 in 2003. Interaction effect between year and treatments was not significant, indicating that the variation in N uptake was consistent under different N and water management in both years.

N use efficiency

Data on rice yields and N uptake for the two years were pooled, as trends were similar. The fertilizer response (AE) curve in quadrant (a) of Fig. 5.2 shows maximum yields at N doses of 150 kg ha^{-1}. Under CI, AE varied between 18.8 and 4.3 kg kg^{-1} and under II between 10.4 and 3.5.

NUE is the slope of the linear part of the curve relating grain yield and N uptake (Fig. 5.2, quadrant (b)). In this experiment, the relation between yield and N uptake started to deviate from the linear at uptake values exceeding 145 (CI) and 169 (II) kg ha^{-1}, indicating that at higher N-availability, other growth factors became limiting (Van Keulen, 1982). Comparison of the CI and II curves shows that in two of the three cases, NUE of II is lower than that of CI, which could hint at some water stress during at least part of the gowing season.

Indigenous soil N supply was about 110 kg ha^{-1} and not significantly different between II and CI (Fig. 5.2, quadrant (c)). At N rates below 225 kg ha^{-1}, average ANR was lower under CI (43%) than under II (49%). At 300 kg N ha^{-1}, ANR dropped to 32 and 39% for CI and II, respectively.

When comparing both rice seasons, NUEs were much higher in 2002 than in 2003 (not shown), *i.e.* the crop produced more grain yield per unit N uptake in 2002, suggesting that factors other than N affected rice yield in 2003, such as unfavorable weather conditions.

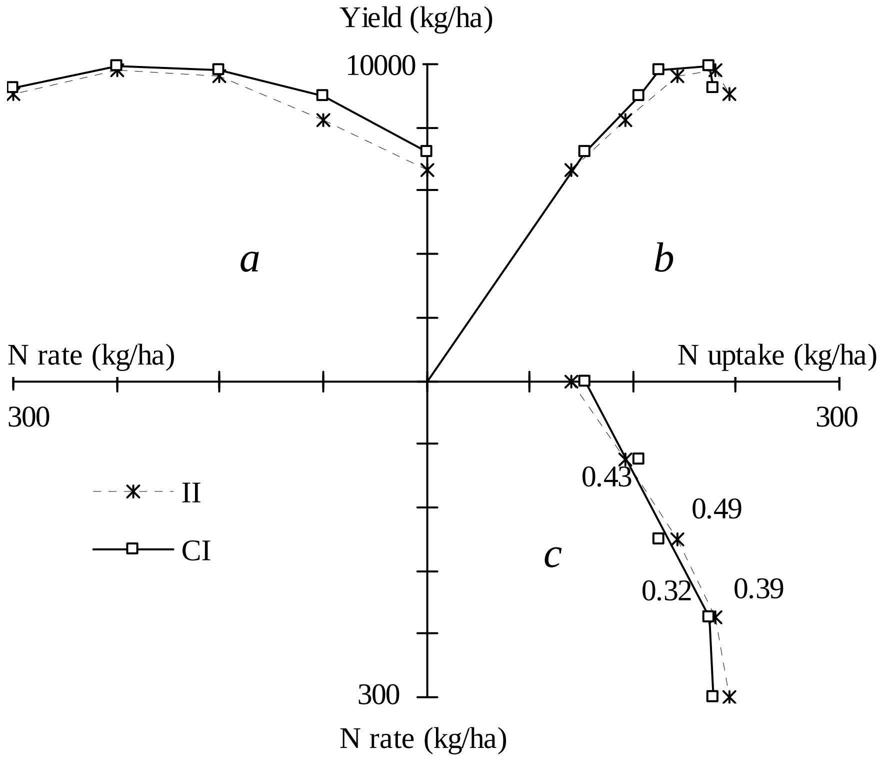


Figure 5.2 *Relationship between N application and yield (quadrant a), N uptake and yield (quadrant b) and N application and N uptake (quadrant c) for the rice seasons in 2002 and 2003 (pooled data from two seasons). The numbers in quadrant c represent mean Apparent Nitrogen Recoveries (ANR, see text for details) of different water management practices, II = intermittent irrigation, CI = conventional flood irrigation (see text for details), below and above 150 kg N ha^{-1}.*

5.4.3 Wheat

Grain yield

Grain yields ranged from 1370 to 3712 kg ha^{-1} on average for the control (0/0 kg N ha^{-1}) and the 300/300 kg N ha^{-1} treatment, respectively. Although wheat yields in the II plots were almost 10% higher than in the CI plots, the difference was not significant. Hence, water management did not (statistically) significantly affect grain yields and yield components in the first wheat season (Table 5.2). In the second season, yields ranged from 1416 to 5721 kg ha^{-1}, grain yield increased almost linearly with increasing N rates, and was closely related to grain number per unit area (R^2 = 0.9618, n = 15), that ranged from 4000 to 15800 per m^2, suggesting a strong N limitation to grain formation in the 0/0 plots. In both seasons, the response of grain number to N rate was significant, though effects were more pronounced in the second season. On average, yields at the fertilizer rates of 150 and 300 kg ha^{-1} were lower in the first season, associated with lower grain numbers per unit area. In both seasons, effects of N rates on the preceding rice crop on wheat yield and yield components were not significant, suggesting no carry-over of residual N between seasons. This even holds for the wheat control plots in the second year, following high N applications in rice.

Table 5.2 The performances of yield components, yield and N uptake of above ground at maturity of wheat under different treatments in 2002-2003 season, and their variation source.

Treatment	Grain no. (per m^2)	1000-kernal-weight (g)	Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})
N rates (kg ha^{-1})				
0	3639	36.4	1328	31
150	7987	35.3	2792	78
300	9084	39.7	3596	109
$LSD_{0.05}$	*582*	*1.6*	*181*	*7*
Irrigation in rice season				
CI	6633	37.1	2462	68
II	7201	37.2	2683	77
	892	*1.3*	*423*	*5.9*
Variation source				
N rates in rice season	NS	NS	NS	NS
N rates in wheat season	**	**	**	**
N rates (kg ha^{-1})				
0	4094	35	1416	30
75	6363	40	2547	57
150	11019	41	4478	111
225	11507	37	4242	122
300	15779	36	5721	184
$LSD_{0.05}$	*3342*	*4*	*1416*	*38*
Variation source				
N rates in rice season	NS	NS	NS	NS
N rates in wheat season	**	*	**	**

*,** significant at 0.05 and 0.01 probability levels; NS not significant.

Aboveground N uptake

Average N-uptake in wheat following II was 9 kg ha^{-1} higher than following CI in the first season (Table 5.2). Particularly wheat in the control plots absorbed more N following rice under II. Nitrogen uptake ranged from 31 to 109 kg N ha^{-1} in the first season, and from 30 to 184 kg in the second and was significantly affected by N rates, but not by the N rates on the preceding rice crop, indicating no carry-over of residual N in either year.

N use efficiency

Grain yields increased with N rates in both wheat seasons (Fig. 5.3, quadrant (a)). In the first season, agronomic N use efficiency (AE) of the 150 and 300 kg N ha^{-1} treatments was 9 kg grain per kg N applied and was not affected by water management in the preceding rice season. AE was on average 16 kg grain per kg N applied in the second season. ANRs in the first season were identical following CI and II in rice: 34 and 27% below and above 150 kg N ha^{-1}, respectively (Fig. 5.3, quadrant (c)), average ANR was 45% in the second season. Grain yield increased with N uptake (Fig. 5.3, quadrant (b)), and NUE was not different for the water management treatments in the rice season, with an average value of 42 kg kg^{-1} in the first season.

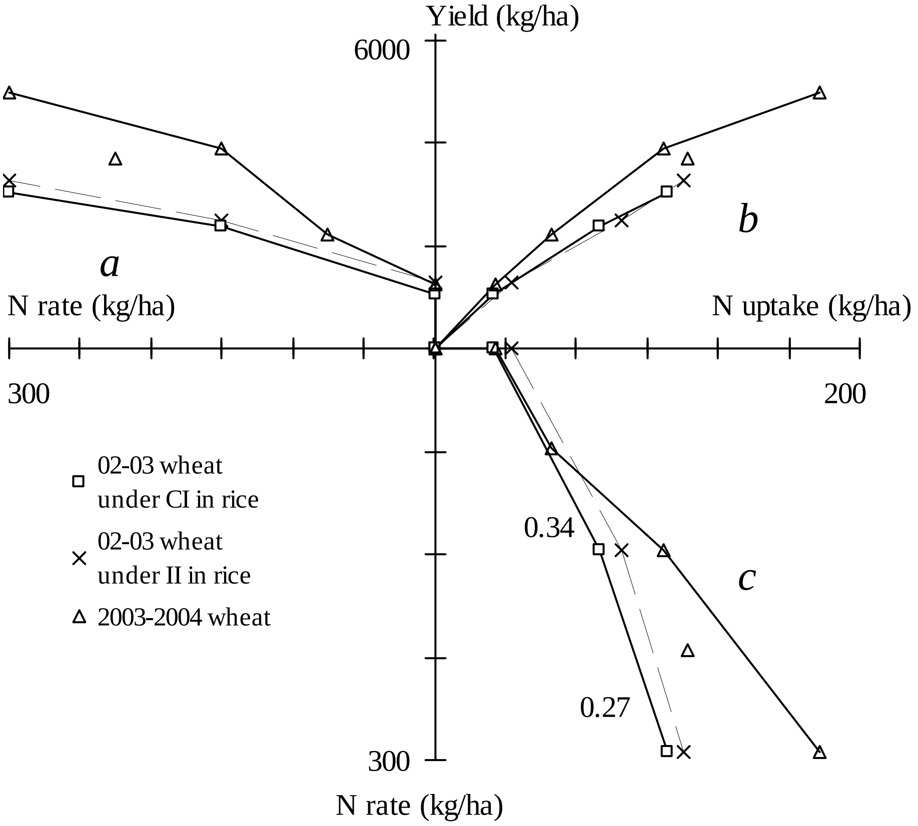


Figure 5.3 Relationship between N application and yield (quadrant a), N uptake and yield (quadrant b) and N application and N uptake (quadrant c) for the wheat seasons. Numbers in quadrant c represent Apparent Nitrogen Recoveries (ANR, see text for details).

5.4.4 Soil nitrogen content

Total soil N

Total N in the 0-40 cm soil layer was variable in the course of the experiment (Table 5.3), but the effects of water and nitrogen management were not significant, while the distribution over the 0-20 and 20-40 cm soil layers hardly changed. In all treatments, soil N content decreased with depth (data not shown).

Table 5.3 Total nitrogen content (%) in the 0-40 cm soil depth in the course of the experiment.

Treatment		After first rice season	Before first wheat season	After first wheat season	After second rice season	After second wheat season
Irrigation	CI	0.180	0.175	0.156	0.166	-
	II	0.188	0.175	0.181	0.157	-
	$LSD_{0.05}$	*0.025*	*0.055*	*0.026*	*0.044*	
N rates	0	0.160	0.164	0.156	0.195	0.163
(kg N ha^{-1})	150	0.203	0.214	0.170	0.155	0.190
	300	0.188	0.167	0.178	0.190	0.178
	$LSD_{0.05}$	*0.045*	*0.067*	*0.033*	*0.070*	*0.072*

'-', data not available.

Soil nitrate

Soil nitrate content varied significantly in the course of the experiment (Fig. 5.4). Directly following harvest of the first rice crop, nitrate content in the surface 40 cm layer was not different between CI and II, while after a fallow period of 17 days, it was higher under II than under CI. Nitrate content was low and not different among N rates after rice harvest, confirming that carry-over of mineral N was limited. Nitrate contents following wheat harvest were much lower than after the first rice season, but not different among the N treatments.

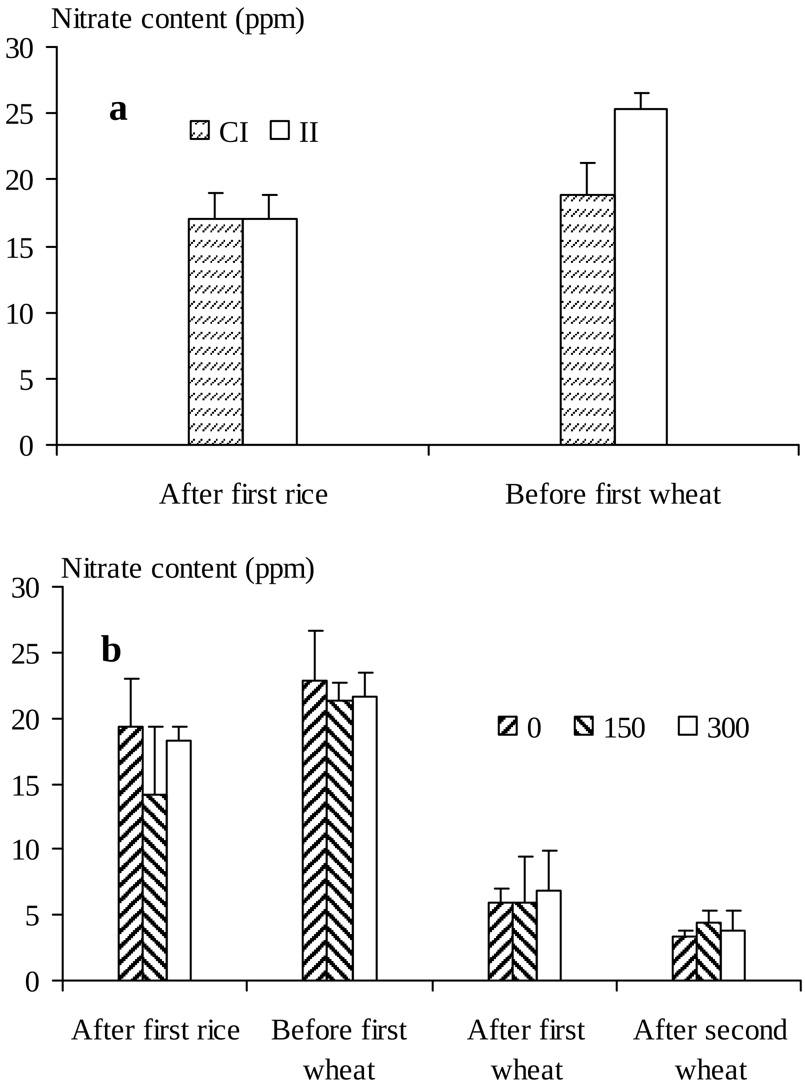


Figure 5.4 Effects of different water management (a) and nitrogen application rates (b) on nitrate content in the 0-40 cm soil depth in the course of the experiment.

5.5 Discussion and conclusions

Intermittent irrigation of rice did not result in significantly lower yields than continuous flooding in the two experimental seasons, confirming previous experiences (Belder *et al.*, 2004; 2005; Cao *et al.*, 2002). However, the slightly reduced yield over the entire range of N rates under II (Fig. 5.2a) could indicate some drought stress. In addition, the lower NUE under II suggests unidentified crop growth limitations at high N rates (Fig. 5.2b). Nitrogen had significant effects on grain yield and yield components of both rice and wheat. In rice, yield responded no further at N rates exceeding 150 kg ha^{-1}, in contrast to wheat, that responded up to rates of 300 kg ha^{-1}, especially in the first season. In general, wheat yields were much lower than those of rice at the same N fertilizer rates. The period between panicle/spike initiation and maturity for both rice and wheat lasted 65 days. However, leaf area duration (the integral of green leaf area over time) in wheat was smaller than in rice, as wheat leaves died well before maturity in contrast to those of rice, which resulted in smaller average crop biomass (5 t ha^{-1} vs. 14.6 t ha^{-1}).

The lower yields of rice in the second season are a consequence of high rainfall and associated low solar radiation, resulting in lower spikelet densities. Two weeks after rice transplanting, in the tillering phase, a three-week heavy rainfall period started. On July 4 and 5, rainfall totalled 200 mm (Fig. 5.1), resulting in complete submergence of the crop for 2 days which might have resulted in lower number of tillers and panicles. Radiation before anthesis was lower in 2003 than 2002 (Table 5.4), resulting in lower growth rates and thus lower spikelet densities (Kropff *et al.*, 1994b). The difference in yield between the two years was also consistent with the difference in photothermal quotient (PTQ), defined by Nix (1976) as the ratio of mean daily radiation for an interval to mean temperature minus a base temperature. PTQ prior to anthesis showed a positive linear relationship to grain yield (Nix, 1976; Islam and Morison, 1992, Ortiz-Monasterio *et al.*, 1994).

Table 5.4 The photothermal quotient (PTQ) and radiation (R) during 20 days prior to panicle initiation (PI-20) to PI and PI to anthesis (A) in rice and 20 days prior to anthesis (A-20) to A in wheat in two seasons.

Season	Rice				wheat	
	PTQ (MJ m^{-2} d^{-1} $^{o}C^{-1}$)		R (MJ m^{-2} d^{-1})		Q (MJ m^{-2} d^{-1} $^{o}C^{-1}$)	R (MJ m^{-2} d^{-1})
	PI-20 to PI	PI to A	PI-20 to PI	PI to A	A-20 to A	A-20 to A
1st season	0.89	0.74	19.5	14.6	1.27	13.8
2nd season	0.58	0.53	11.6	12.4	1.42	16.9

Photothermal quotient is defined as the ratio of the mean daily total incident solar radiation for an interval to the mean temperature less the base temperature (Nix, 1976). The base temperature for japonica rice is 8 °C and for wheat 4.5 ^{o}C.

In the subsequent wheat season, yields on rice II plots tended to be higher, but effects were not significant. In contrast, nitrogen uptake of wheat in the first season was higher in these rice II plots, associated with higher soil nitrate contents before the wheat season (Fig. 5.4). N rates in rice did not affect wheat yields, suggesting that there was little N carry-over from the preceding rice season to the wheat season, which is supported by soil total nitrogen and nitrate contents after rice harvest. This is consistent with results from Ladha *et al.* (2000a), showing no residual effect on rice grain yield and N uptake after eight years of urea-N application. Fan *et al.* (2005) did neither observe differences in soil mineral N after rice harvest following different N rates in rice. In contrast to our results, they observed differences in residual mineral N following differential N rates on wheat. These divergent results may be due to differences in experimental conditions (soil and climate).

In the 2002-2003 season, wheat yields were very low compared to 2003-2004 and to the yields (4500-6000 kg ha^{-1}) commonly realized at application rates of 135-315 kg N ha^{-1} after rice in South Jiangsu (Wang *et al.*, 2003a; Xu and Wu, 1999). The lower radiation and PTQ during the 20 days prior to anthesis in the first wheat season (Table 5.4) resulted in much lower grain numbers (Nix, 1976; Fischer, 1985; Bindraban *et al.*, 1998), which may have created sink limitations during grain filling.

The pooled rice data showed higher ANRs under II than under CI, in line with other reports (Belder *et al.*, 2005). Low ANRs may have been caused by higher N losses under CI due to de-nitrification and ammonia volatilization (Cai *et al.*, 1986; Zhu *et al.,* 1989). Water management treatments in the previous rice season had no effect on ANR of wheat, but N uptake of wheat following II was higher than that following CI, because of differences in indigenous N supply (Table 5.2).

Dobermann *et al.* (2003a) reported strong variations in indigenous soil N supply in different areas of Asia, with a maximum value of 80 kg ha^{-1} in irrigated rice in Jinhua, Zhejiang Province in Southeast China. In our experiment, indigenous soil N supply was 130 kg ha^{-1} in the first season and 91 kg ha^{-1} in the second, which was fully reflected in differences in rice yield of the control plots between the two years, *i.e.* 7193 kg ha^{-1} in 2002 and 6658 kg ha^{-1} in 2003. Potential indigenous N supply in rice in Southeast China may thus be substantially higher than the widely accepted level of 80 kg N ha^{-1}, which should have consequences for nitrogen recommendations in rice (Witt and Dobermann, 2004). Indigenous N supply was much lower in the wheat season, *i.e.* about 30 kg ha^{-1} (Table 5.2). This difference in indigenous soil N supply should be accounted for in nutrient management of RW systems.

6 Modelling nitrogen and water dynamics in rice-wheat rotations

Q. Jing[1,2,3], H. van Keulen[2,3], H. Hengsdijk[2]

[1] Key Lab of Crop Growth Regulation, Ministry of Agriculture, Nanjing Agricultural University, Nanjing 210095, China
[2] Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA Wageningen, the Netherlands
[3] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, the Netherlands

Abstract

Rice - wheat (RW) is a major cropping system in China, occupying 9-13 Mha. A main feature of RW rotations is the alternation of aerobic and anaerobic soil conditions. This alternation of flooded and non-flooded soil conditions is conducive to N emissions, especially with the current high N rates in RW systems. To design alternative management systems, better understanding of the processes underlying emissions is required. For that purpose, a RW simulation model (RIWER) was developed, on the basis of existing crop, water and soil organic matter models, describing the relevant soil processes under both anaerobic and aerobic conditions. RIWER is evaluated using two years of data from a rice wheat rotation experiment in Nanjing, China. Assessment of model performance, on the basis of graphical comparison and goodness-of-fit parameters, showed that RIWER performs well in simulating total aboveground biomass, N uptake and soil inorganic N content. The RIWER modelling framework needs further testing, but offers a promising operational tool for designing sustainable RW systems, combining environmentally-friendly production methods and high yields.

Keywords: soil; cropping systems; organic matter; decomposition; denitrification.

6.1 Introduction

Rice-wheat systems in China, occupying between 9-13 Mha (Dawe *et al.*, 2004; Huke *et al.*, 1993; Ladha *et al.*, 2003; Timsina and Connor, 2001), are located mainly in

Jiangsu, Anhui, Sichuan and Hubei provinces along the Yangtse River and provide the bulk of the cereals required for feeding its population. To safeguard food security for the population that increases annually with 15 million, more cereals need to be produced. In the last decades, yield increases have been mainly the result of introduction of improved varieties, combined with increasing agrochemical inputs (Hafner, 2003; Richter and Roelcke, 2000; Tong *et al*., 2003). Recent studies suggest that yield increases in both wheat and rice decline, while their production has been associated with environmental problems such as soil erosion and pollution of surface water with nutrients and biocides (Cassman *et al*., 1995; Li *et al*., 2000; Tong *et al*., 2003; Zhang *et al*., 1996; Zhu *et al*., 2000). Crop management in rice-wheat (RW) systems therefore should be modified towards more sustainable systems that combine environmental-friendly production methods and high yields.

A main characteristic of RW rotations is the alternation of aerobic and anaerobic soil conditions (Timsina and Connor, 2001), which strongly affects microbial C and N dynamics (Fierer and Schimel, 2002), and results among others in a temporary increase in inorganic soil nitrogen during rewetting (Appel, 1998; Lundquist *et al*., 1999; Qiu and McComb, 1996). Excess soil mineral N that cannot be taken up by the crop may be lost through denitrification (Qiu and McComb, 1996; Reddy *et al*., 1989). These complex processes need to be better understood and quantified, as a basis for improvements in crop management in RW systems that lead to high yields and high nitrogen and water use efficiencies. Modelling is a useful and effective tool for explicitly describing the relationships among the various components of complex systems. Modelling contributes to increased insight into relevant processes and their interactions, and can be applied to study effects of crop management, and to explore possible consequences of management modifications (Van Keulen, 2001). The challenges for application of existing models to simulate RW systems are the regular alternation between anaerobic and aerobic conditions and its consequences for decomposition of soil organic matter, nitrification and denitrification (Probert, 2002). The crop growth models CERES-Rice and CERES-Wheat (CERES: Crop Estimation through Resource and Environment Synthesis) have been applied for studying RW systems in northern Bangladesh and northwest India (Sarkar and Kar, 2006; Timsina *et al*., 1998). Both, the rice and the wheat model performed satisfactorily under both water and N non-limiting conditions. However, available evidence suggests that both crop models do not perform well in resource-limited situations, while the soil organic model did not perform well under anaerobic conditions (Timsina and Humphreys, 2006). Especially, understanding of soil organic matter decomposition under anaerobic conditions is limited, since most of the existing soil organic matter models have been developed for aerobic conditions (Shibu *et al*., 2006). Simulation of RW rotations requires models that describe the dynamics of, and at times, extreme changes in soil hydrological conditions associated with growing continuously flooded rice in sequence with wheat grown in non-saturated soil, and their profound impact on nutrient dynamics, especially N (Timsina and Humphreys, 2006).

In this study, a modelling framework for rice-wheat rotations (RIWER) is developed, taking into account the specific characteristics of water and nitrogen dynamics in these systems. Our framework is based on the Wageningen models (Bouman *et al.*, 1996; Van Ittersum *et al.*, 2003), namely two crop growth models ORYZA2000 (Bouman *et al.*, 2001) and SWHEAT (Van Keulen and Seligman, 1987), and a soil model that combines the modules PADDY and DRSAHE with the soil organic matter model SOM (Jongschaap, 1996), adapted for both aerobic and anaerobic conditions. The rice model ORYZA2000 and the wheat model SWHEAT have been evaluated for potential and water/nitrogen limited conditions in different environments (Belder *et al.*, 2007; Boling *et al.*, 2007; Bouman and Van Laar, 2006; Jing *et al.*, 2007; Van Keulen and Seligman, 1987). RIWER is evaluated in this study using experimental field data of RW rotations in China.

6.2 Model description

6.2.1 Structure

RIWER operates within the simulation shell FSE3.0 (FORTRAN Simulation Environment; Fig. 6.1), developed by Van Kraalingen (1995). The FSE-driver (outer circle) checks the model components and continues execution, with a daily time step, until a user-defined end time is reached. If multiple runs are defined, the FSE-driver restarts execution of all modules with new values for variables or parameters, specified in the rerun file.

RIWER consists of a management module (MAN), two crop modules ORYZA2000 and SWHEAT, a soil module including the water module PADAHE and the soil organic matter module (SOM). The latter two in combination, simulate inorganic soil nitrogen processes (Fig. 6.2). Each module has its own data file.

During execution, the various modules in RIWER run individually, and they mutually interact by exchanging daily values of variables, such as mineralized N, soil water content, daily crop N uptake, transpiration, *etc*. Crop growth modules for both rice and wheat are initialized annually, and discontinue execution at harvest time. In contrast, the soil module continues execution during the fallow period, until the user-defined end time.

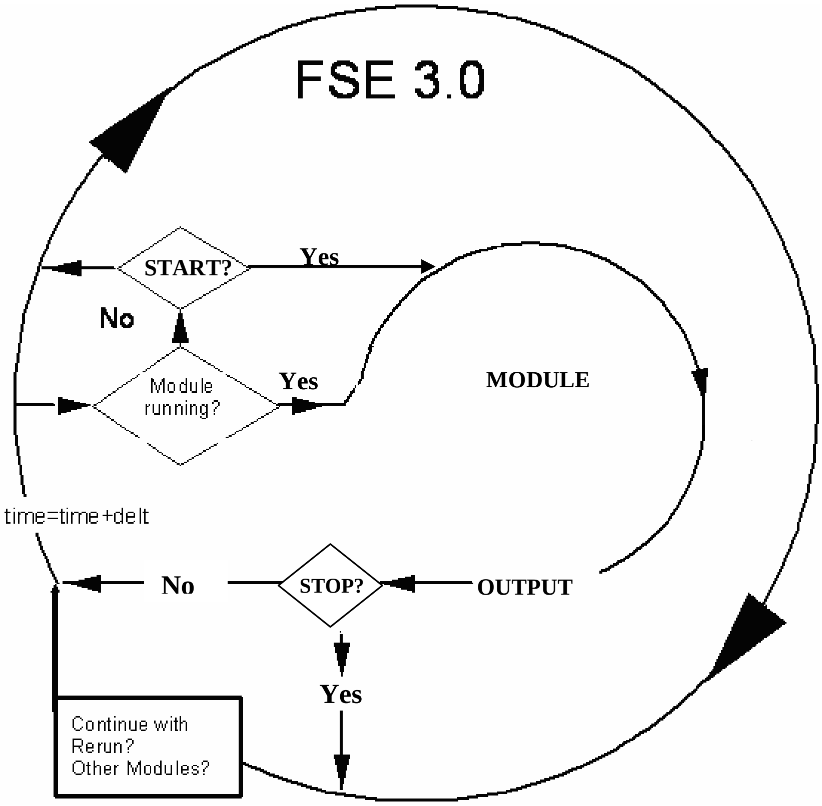


Figure 6.1 Structure of the FSE3.0 (Fortran Simulation Environment) shell to drive modules.

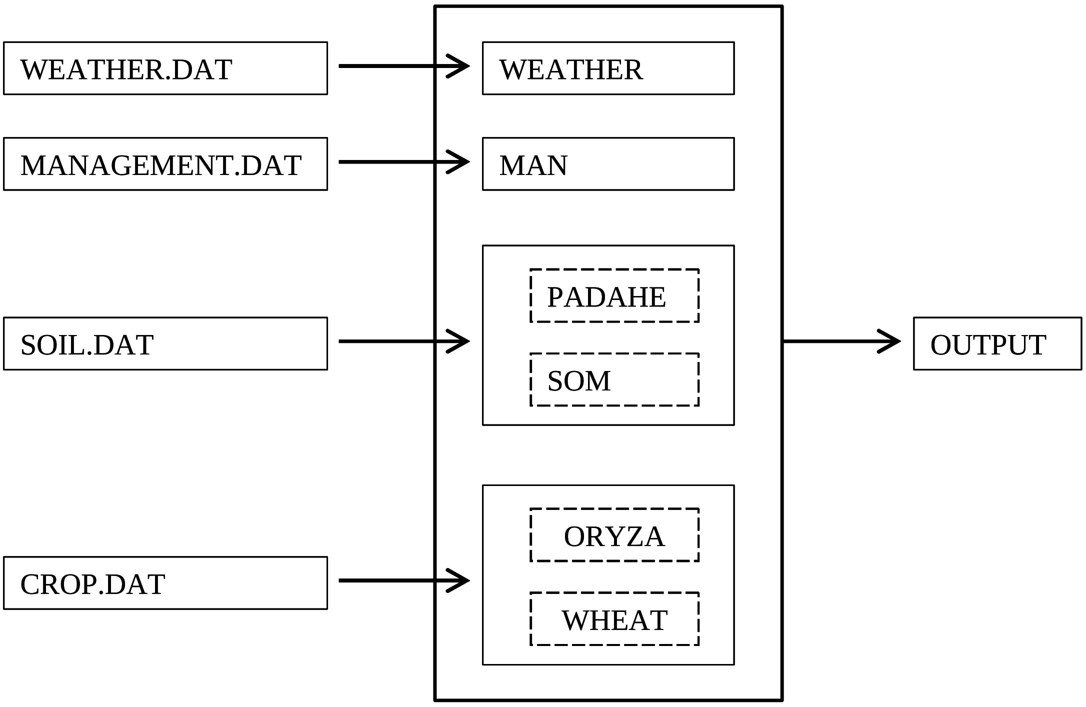


Figure 6.2 Structure of the rice wheat rotation model (see text for explanation). Arrows indicate flows of information.

6.2.2 Crop modules

ORYZA2000 is an ecophysiological crop model, described in detail by Bouman *et al.* (2001). Here, only a brief description is provided. ORYZA2000 simulates growth and development of rice for potential, water-limited and nitrogen-limited production situations. It has been evaluated under nitrogen- and/or water-limited conditions in the Philippines (Bouman and Van Laar, 2006), Indonesia (Boling *et al.*, 2007) and China (Belder *et al.*, 2007; Feng *et al.*, 2007; Jing *et al.*, 2007). In this study, a soil organic matter module (SOM, see following section) is linked to ORYZA2000 to replace the original N module. Actual crop N uptake is the minimum of available soil nitrogen and crop demand. It is assumed that all mineral nitrogen (nitrate and ammonia) in the wet part of the rooted zone is available to the well-rooted rice crop within a relatively short time, either through mass flow or diffusion (Seligman *et al.*, 1975). Uptake by mass flow is driven by transpiration:

$$N_{mass} = \sum_{i}^{n} W_{mass\,i} \times N_{c\,i}$$

where, W_{massi} is mass flow of water to the roots in i-th soil compartment, N_{ci} is the concentration of mineral N in i-th soil compartment.

When total uptake by mass flow does not meet total demand for nitrogen of the rice crop, the remaining demand can be met by diffusion when mineral nitrogen is available. Diffusion stops when translocation of carbohydrates to the root system ceases, because available energy then limits active uptake of nitrogen. The overall equation for uptake by diffusion is:

$$N_{m-d} = \begin{cases} \max(0, N_d - N_{mass})/\tau & DVS < 1.0 \\ 0 & otherwise \end{cases}$$

where, N_d is total crop N-demand, τ is time constant for diffusion of soil mineral nitrogen to the roots, DVS is development stage of rice.

SWHEAT is a similar ecophysiological crop model, developed for aerobically grown wheat crops and simulating dry matter accumulation, phenological development, assimilate distribution, and organ formation (Van Keulen and Seligman, 1987). It takes into account the effects of moisture and nitrogen deficiency on growth, organ formation and yield. The model uses an integration time step of one day.

Dry matter accumulation starts from calculating potential gross CO_2 assimilation as a function of daily radiation and total green plant area, based on an exogenously defined photosynthesis-light response curve of individual leaves, characterized by its initial light use efficiency and the diffusion limited maximum assimilation rate at high light intensities (Goudriaan and Van Laar, 1978). The effect of temperature on gross assimilation is taken into account through a reduction in the light-saturated assimilation rate when daytime air temperatures are below 10 °C. Leaf nitrogen status also affects light-saturated assimilation rate. Soil moisture availability is accounted for by assuming a proportional relation between the reduction in transpiration and in gross CO_2 assimilation. Respiration is subdivided into two components: maintenance respiration is calculated as a fraction of plant dry weight, taking into account the effect of temperature and nitrogen content; growth respiration is expressed as the conversion efficiency from assimilates into structural plant material, taking into account the composition of the material formed. Phenological development, from germination to final maturity and senescence, is described as a function of accumulated temperature. The life cycle of the plant is divided into two major development phases, before and after anthesis. Germination is treated simply as a function of time and soil moisture conditions. Assimilate allocation is defined as a function of development stage and is affected by moisture stress (transpiration deficit in the present model) and by the nitrogen status of the plant, expressed by leaf nitrogen content. The number of grains depends on the number of antecedent organs, florets, spikelets, spikes and tillers. The rate of organ initiation at any stage depends on the rate of carbohydrate flow to the meristematic sites and the minimum carbohydrate requirement to produce a viable organ. Temperature influences the number of organs formed indirectly by determining the duration of the phenological phase and directly by its influence on the formation rate. Nitrogen availability and moisture stress affects organ number indirectly by their effects on development rate and on gross assimilation.

6.2.3 Water module

The water module PADAHE combines two water balance modules, *i.e.* PADDY and DRSAHE. PADDY simulates water dynamics during the rice season and DRSAHE during the wheat season and fallow period. At the onset of flooding and at rice harvest the model switches the water modules, while exchanging the relevant state variable values.

PADDY is a one-dimensional soil-water balance model that can be used for both puddled and non-puddled rice soils (Bouman *et al.*, 2001; Wopereis *et al.*, 1996), and has been evaluated for both, rainfed (Boling *et al.*, 2007) and irrigated rice (Belder *et al.*, 2007). Extraction of water from the top soil layer is by transpiration and evaporation, while water is supplied to the first layer via rainfall and/or irrigation. When a standing water layer is present, vertical water flow through the profile is set to a user-defined percolation rate, either fixed, or defined as a function of groundwater table depth. In the presence of a puddled topsoil, percolation rates are calculated dynamically from hydraulic conductivity characteristics of the plow sole (the bottom layer of the puddled topsoil) and the non-puddled subsoil. The conductivity characteristics are expressed by either 'Van Genuchten'-parameters (Van Genuchten, 1980) or by parameters of a power function. Without a standing water layer, incoming water (rainfall and/or irrigation) is redistributed by calculating for all layers gain and loss terms, starting with the top layer. All water in excess of field capacity is drained from the layer, however, restricted to a maximum rate equal to the saturated hydraulic conductivity of the layer; if the soil profile has one or more soil layers restricting water flow, *e.g.* a hardpan as a result of puddling, then the fluxes into and out of the layer are compared: if downward flow out of the layer is 'too low', the excess water is redistributed upward. Groundwater is assumed to remove all water draining out of the profile and can either be below the soil profile (deep drainage) or within the profile itself. Capillary rise of water from the groundwater table is calculated on the basis of soil moisture tension in each soil layer, using modified procedures from WOFOST (Supit and Van der Goot, 2003).

DRSAHE is a so-called 'tipping bucket' water balance model, developed for free-draining 'upland' soils with a deep groundwater table (Penning de Vries *et al.*, 1989; Stroosnijder, 1982; Van Keulen, 1975; Van Laar *et al.*, 1997). DRSAHE has been evaluated for wheat (Jongschaap, 1996; Van Keulen and Seligman, 1987). The water balance processes considered in DRSAHE are infiltration, percolation, evaporation, transpiration and downward distribution. Upward water flow (capillary rise from a groundwater table) is disregarded, as is lateral in- or outflow of water. The soil profile is divided into a number of homogenous layers, of which thickness and physical characteristics are model inputs. A maximum of 10 layers may be defined without restrictions to their thickness, as long as the sum of the thicknesses of all layers slightly exceeds maximum rooting depth. Vertical inflow and outflow of water in each layer are simulated by assuming that the layers are filled up to field capacity from the top one downwards, the excess draining into the next layer or out of the profile. Inflow into the first layer is from rainfall and/or irrigation. Water is extracted from the layers by evaporation and transpiration.

6.2.4 Soil organic matter module

SOM simulates soil organic matter dynamics under aerobic conditions, governed by soil temperature and moisture content (Jongschaap, 1996). Organic matter is partitioned into a labile and a stable fraction (Fig. 6.3). Dead plant material and added crop residues, *i.e.* roots and other plant organs, are partitioned among decomposable (DPM), structural (SPM) and resistant (RPM) pools. Partitioning factors depend on the C/N-ratio of the added organic material. These fresh materials decay according to first-order dynamics to labile organic matter (Table 6.1). At harvest, living roots are treated like dead plant material in the layer in which they occur. Crop residues, left in the field after harvest, are ploughed in at a specified depth.

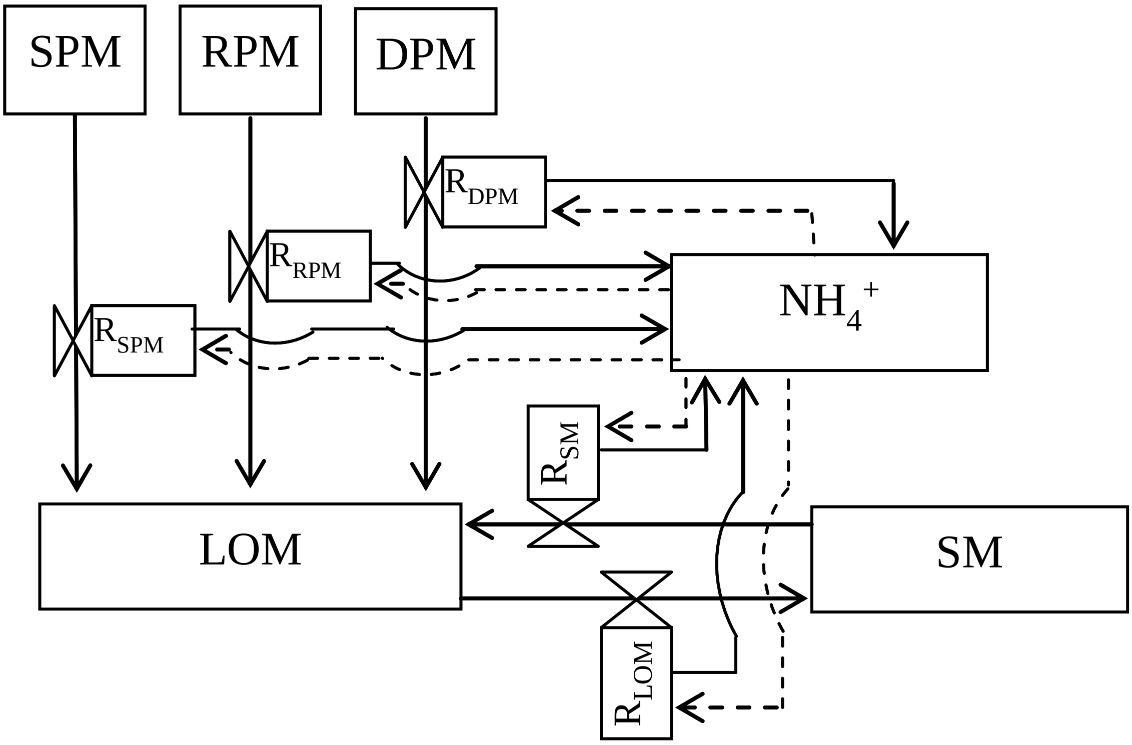


Figure 6.3 Relational diagram of the soil organic module SOM. LOM-labile organic matter, SM-stable organic matter, DPM-decomposable plant material, SPM-structural plant material, RPM-resistant plant material. Dashed arrows indicate immobilization processes.

Table 6.1 First-order rate constants for the decomposition of organic matter under aerobic and anaerobic conditions.

Material	Substrates	Aerobic	Anaerobic	Unit	Reference
Rice	Labile	0.0054	0.0024	d^{-1}	Reddy *et al.*, 1980
	Stable	0.0013	0.0003	d^{-1}	
Alfalfa	Labile	0.123	0.118	d^{-1}	Gale and Gilmour, 1988
	Stable	0.059	0.024	d^{-1}	
Plant	Average	0.015	0.005	d^{-1}	Martin and Reddy, 1997
Cattail and	Litter	0.0028	0.0009	d^{-1}	DeBusk and Reddy, 1998
sawgrass	Peat	0.0008	0.0003	d^{-1}	
Soil native	Average	0.0004	0.00006	d^{-1}	Bridgham *et al.*, 1998[1]
Rice	Average		0.001-0.04	d^{-1}	Chowdary *et al.*, 2004
	Average		0.012-0.019	d^{-1}	Watanabe, 1984

[1] Adapted from the reported values.

The stable and labile organic matter pools represent different fractions of organic matter. Turnover of soil carbon and nitrogen between labile and stable organic matter pools is described by first-order equations. The rate of decomposition of organic matter is highest at a moisture content of 60%, and decreases at both, lower or higher moisture contents (De Neve and Hofman, 2002; Pal and Broadbent, 1975; Thomsen *et al.*, 1999; Wang *et al.*, 2003b). In submerged soils, oxygen is almost absent due to the much slower oxygen diffusion in water (Brune *et al.*, 2000), and anaerobic microbes, using nitrate as electron acceptor take over decomposition, changing the relative importance of various decomposition processes (Shibu *et al.*, 2006). Therefore, decomposition of organic substrates under anaerobic conditions is slower than under aerobic conditions (Bird *et al.*, 2003; Dobermann and Witt, 2000; Jamu and Piedrahita, 2002; Sahrawat, 2004). In RIWER, SOM is adapted for anaerobic conditions through the effect of soil moisture content on decomposition rate, which is reduced by a factor of 0.35 at soil moisture contents above field capacity (Fig. 6.4).

During decomposition of fresh material and soil organic matter, mineral N is released and concurrently part of the inorganic N is immobilized in microbial biomass, depending on the availability of inorganic nitrogen in the soil.

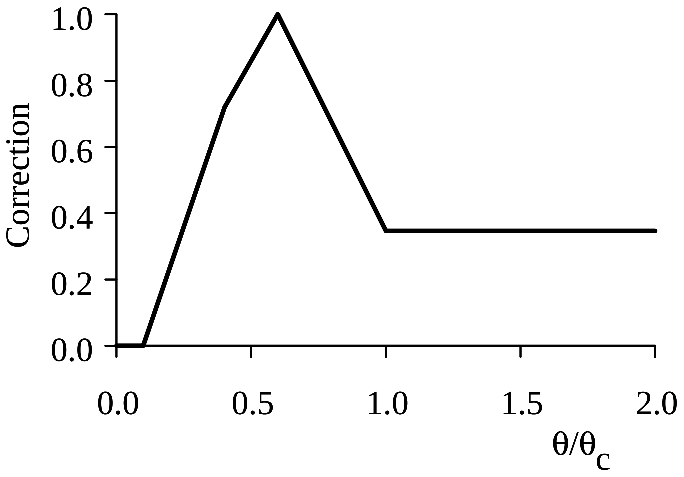


Figure 6.4 Multiplication factor for relative rate of decomposition of organic matter as a function of relative soil moisture content. θ is actual soil water content and θ_c is soil water content at field capacity, both in the same units.

6.2.5 Dynamics of inorganic N

Inorganic soil N comprises two pools, *i.e.* NH_4^+ and NO_3^- (Fig. 6.5), ignoring the intermediate states, as they are unstable (NO_2^-) or gaseous (NO, N_2O and N_2). Both, NH_4^+ and NO_3^- can be taken up by crops. NH_4^+ originates mainly from mineralization and fertilization and is converted to NO_3^- through nitrification. In turn, NO_3^- may be denitrified, depending on the availability of oxygen in the soil. As oxygen concentration in the soil is related to water content (Schurgers *et al.*, 2006), in the model the transformations of ammonia and nitrate depend on water content. Rainfall is an additional inorganic nitrogen source, added as NH_4^+ in this model. Nitrogen in drainage water is assumed to consist of NO_3^-, which allows calculation of nitrogen leaching.

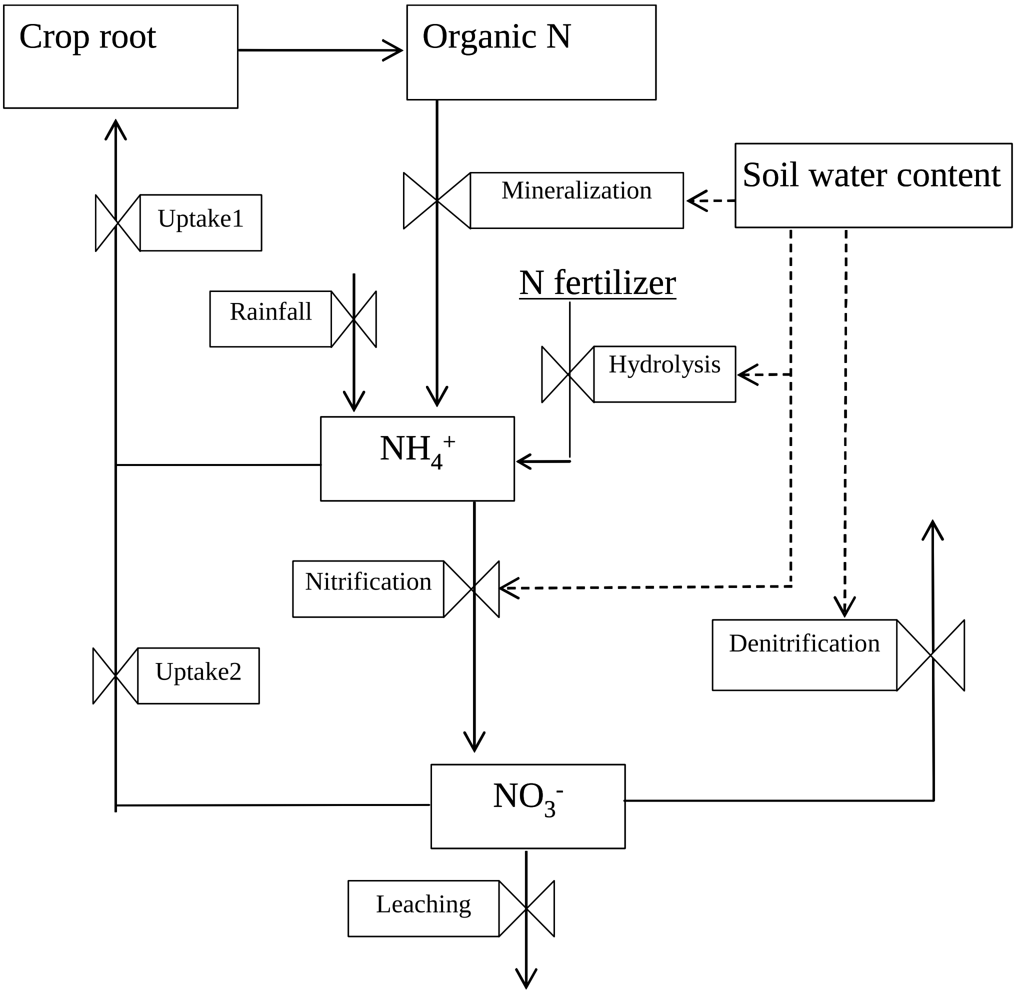


Figure 6.5 Relational diagram of mineral N flows in RIWER.

Urea hydrolysis

When urea ($CO(NH_2)_2$) is applied, it hydrolyzes to NH_4^+ and HCO_3^- ions in about one week (Katyal and Gadalla, 1990), following first order kinetics (Chowdary *et al.*, 2004):

$$RUrea = K_h \times [Urea_t] \qquad \text{(eqn 6.1)}$$

where, K_h is the relative rate of urea hydrolysis.

Nitrification

Ammonium is transformed into nitrate when oxygen is present in the soil. Under aerobic conditions, most of the mineral nitrogen is present in the form of nitrate, while under anaerobic conditions the dominant form is ammonium. The rate of nitrification, RNH_4^+, is affected by soil water content.

$$RNH_4^+ = K_n \times [NH_4^+] \times F_w \qquad \text{(eqn 6.2)}$$

where, K_n is the relative rate of nitrification, and F_w is a correction factor for soil water content.

Denitrification

In anaerobic soil layers, NO_3^- is the oxygen donor during organic matter decomposition, *i.e.* NO_3^- is reduced to gaseous NO, N2O, and N2 (Revsbech *et al.*, 1999). One third of the applied N fertilizer may be lost in gaseous form (Reddy *et al.*, 1989). Under anaerobic conditions, NO_3^- may become limiting for denitrifying bacteria due to competition of rice roots (Reddy and Patrick, 1986). In SOM, denitrification is described following Heinen (2006), *i.e.* as a function of soil nitrate content, soil temperature and soil water content:

$$RNO_3^- = Kd \times [NO_3^-] \times f_T \times f_w \qquad \text{(eqn 6.3)}$$

$$f_T = Q_{10}^{(T-T_r)/10} \qquad \text{(eqn 6.4)}$$

$$f_w = \begin{cases} 0 & S < S_t \\ \left(\frac{S-S_t}{S_m-S_t}\right)^w & S_t \le S \le S_m \\ 1 & S_m < S \end{cases} \qquad \text{(eqn 6.5)}$$

where K_d is the relative rate of denitrification, f_T and f_w are dimensionless reduction factors, describing the effect of soil temperature and water content, respectively. T is soil temperature, T_r is a reference temperature where $f_T = 1$. Q_{10} expresses the increase in f_T at an increase in T of 10 °C, with the value of 2.2. S is a dimensionless factor, expressing the relative water-filled pore space; S_m is S above which $f_w = 1$, set to 1, S_t is set to field capacity. The parameter w is a measure for the steepness of the curve, set to 1.5.

6.3 Model evaluation

Model evaluation is based on results of experiments carried out at Jiangpu experimental station of Nanjing Agricultural University at Nanjing, P.R. China (32° 04′ N, 118° 48′ E) from 2002 to 2004, on an Anthrosol (FAO, 2007) with pH 7.1, Olsen phosphorus 23.9 mg kg^{-1} (Sims, 2000) and available potassium 95.7 mg kg^{-1} (Cox *et al.*, 1999). Japonica rice cultivar Wuxiangjing9 and wheat cultivar Yangmai10 were used in both experimental years. N rates and distributions are shown in Table 6.2. See for a detailed description of the experimental set up (Jing *et al.*, 2005).

Table 6.2 N rates and splits[1] *in the rice and wheat seasons.*

N rates (kg ha^{-1})	Distributions	
	Rice	Wheat
0	0	0
150	90, 30, 30	90, 60
300	180, 60, 60	180, 120

[1] Splits at transplanting, 15 days after the onset of stem elongation and 25 days later in the rice season; at sowing and stem elongation in the wheat season.

RIWER is evaluated with respect to total aboveground dry matter production and total N uptake, using data of the first rice-wheat sequence for calibration, those of the second for validation. Due to the limited availability of measured belowground data, performance of RIWER could only be evaluated for soil inorganic N content in the calibration set. The model is evaluated by comparing observed and simulated data, using a combination of graphical presentations and statistical measures, following the methods described by Bouman and Van Laar (2006).

The model, including crop and soil parameters used, is available from the corresponding author or at http://www.pps.wur.nl/UK/Dissertations/.

6.3.1 Model performance

Simulated and measured total aboveground crop biomass and N uptake are graphically presented in Fig. 6.6 for the calibration set and in Fig. 6.7 for the validation set. Generally, the model satisfactorily reproduces measured total aboveground biomass and N uptake at different N fertilizer levels, and hence the effects of sub-optimal nitrogen supply in both rice and wheat, in the calibration as well as the validation set. Goodness-of-fit parameters for the crop variables are given in Table 6.3. The Student's test values indicate that all simulated values are similar to measured values with 95% confidence, in both the calibration and validation set. The slope (α) for total biomass is close to 1, and the coefficients (R^2) are all significant. For wheat, the means of measured values are similar to the mean simulated values, as well as the standard deviations. For rice, $RMSE_a$ and $RMSE_n$ are 2-3 times higher than S.E. and CV values, and for wheat, they are similar and smaller, respectively.

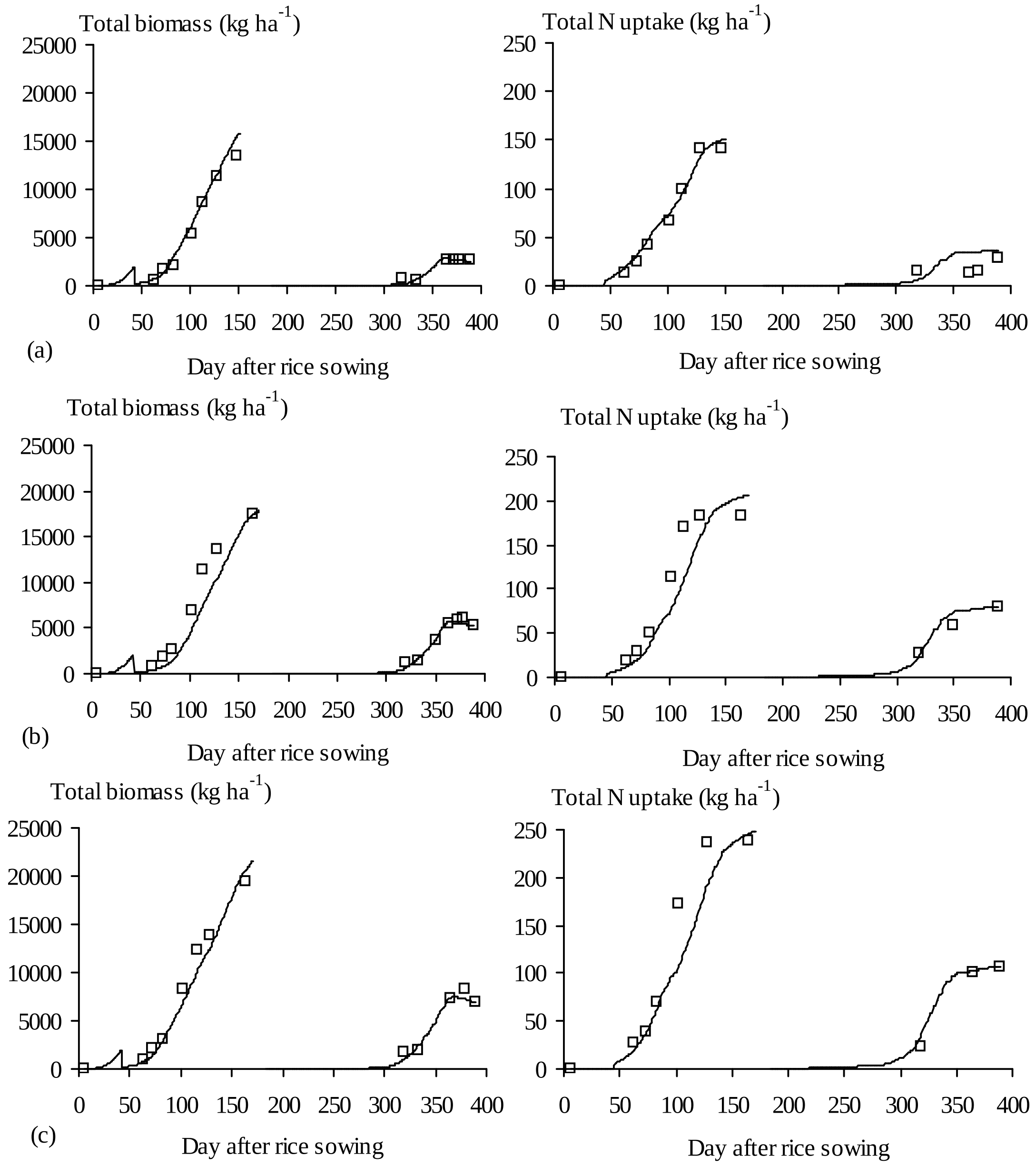


Figure 6.6 Simulated (lines) and measured (symbols) total aboveground dry biomass and N uptake for the calibration set (2002-2003 season). (a) 0 kg N ha^{-1} in rice season and 0 kg N ha^{-1} in wheat season; (b) 150 kg N ha^{-1} in rice season and 150 kg N ha^{-1} in wheat season; (c) 300 kg N ha^{-1} in rice season and 300 kg N ha^{-1} in wheat season.

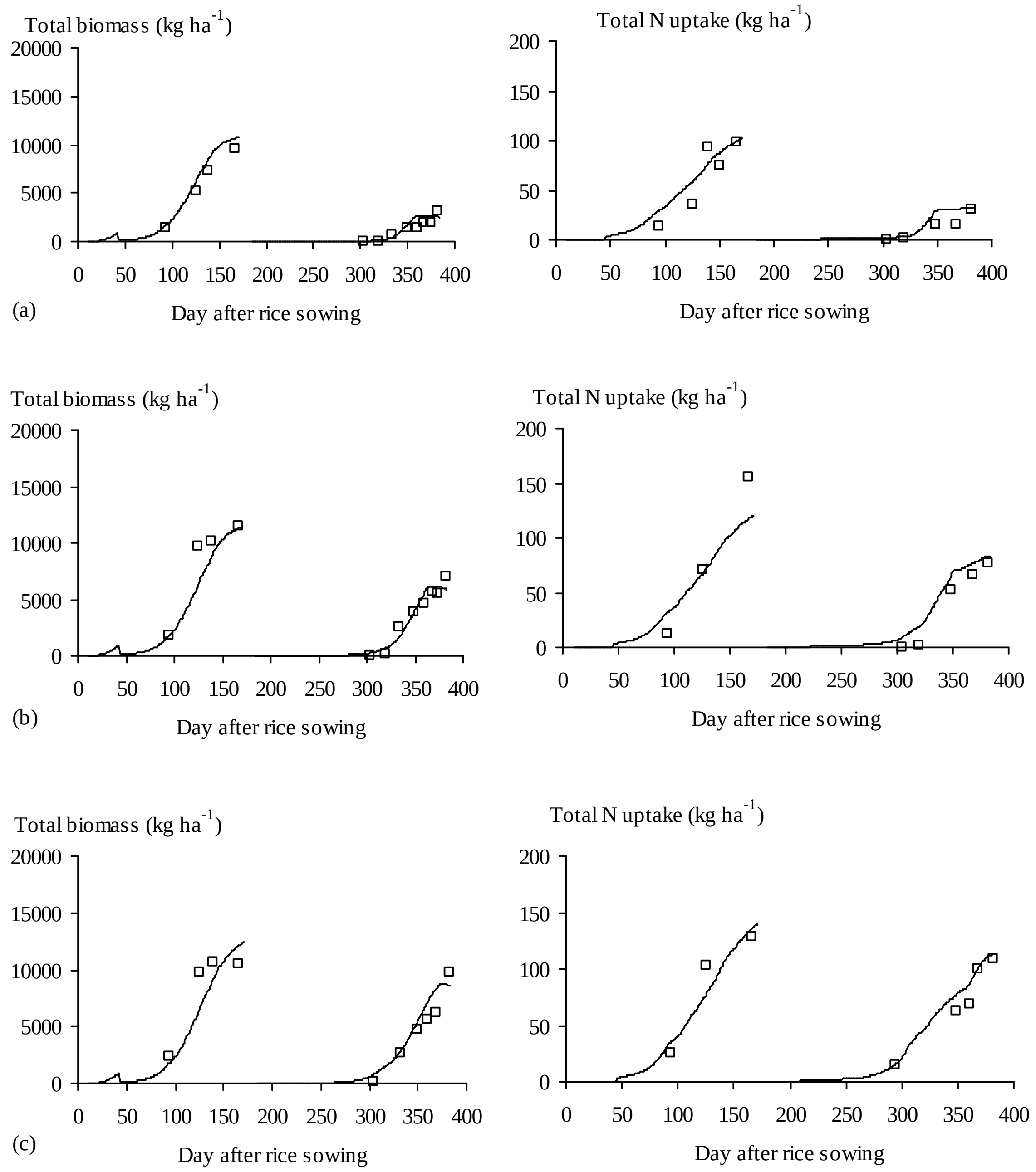


Figure 6.7 Simulated (lines) and measured (symbols) total aboveground dry biomass and N uptake for the validation data set (2003-2004 season). (a) 0 kg N ha^{-1} in rice season and 0 kg N ha^{-1} in wheat season; (b) 150 kg N ha^{-1} in rice season and 150 kg N ha^{-1} in wheat season; (c) 300 kg N ha^{-1} in rice season and 300 kg N ha^{-1} in wheat season.

Table 6.3 Evaluation results of model simulations of crop variables over entire seasons for the calibration and validation data sets.

Crop variable			N	X_{mea} (S.D.)	X_{sim} (S.D.)	P(t)	α	β	R^2	RMSE absolute	RMSE (%) normalized	S.E.	cv (%)
Calibration set													
Rice	Total biomass	(kg ha^{-1})	21	7518 (5994)	6927 (6038)	0.38*	0.98	-421	0.94	1550	21	458	7
	Total N uptake	(kg ha^{-1})	20	103 (75)	92 (70)	0.31*	0.88	1	0.90	26	25	14	16
Wheat	Total biomass	(kg ha^{-1})	18	3746 (2425)	3595 (2389)	0.43*	0.97	-44	0.97	424	11	524	18
	Total N uptake	(kg ha^{-1})	10	47 (37)	53 (34)	0.35*	0.90	11	0.92	11	24	10	26
Validation set													
Rice	Total biomass	(kg ha^{-1})	12	7518 (3784)	7067 (3730)	0.39*	0.88	418	0.80	1693	23	936	11
	Total N uptake	(kg ha^{-1})	11	74 (48)	74 (35)	0.49*	0.68	24	0.86	19	26	10	14
Wheat	Total biomass	(kg ha^{-1})	22	3324 (2770)	3605 (2820)	0.38*	0.97	377	0.91	874	26	664	15
	Total N uptake	(kg ha^{-1})	14	49 (38)	62 (36)	0.19*	0.90	17	0.94	6	12	17	27

N, number of measured/simulated data pairs; X_{mea}, mean of measured values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of whole population; P(t), significance of paired *t* test; α, slope of linear relation between simulated and measured values; β, intercept of linear relation between simulated and measured values; R^2, adjusted linear correlation coefficient between simulated and measured values; $RMSE_n$ normalized root mean square error between simulated and measured values (%); $RMSE_a$, absolute root mean square error between simulated and measured values; S.E. standard error (the same unit as variable); CV, coefficient of variation (%) for measured crop variables.

In a column, * means simulated and measured values are the same at 95% confidence level.

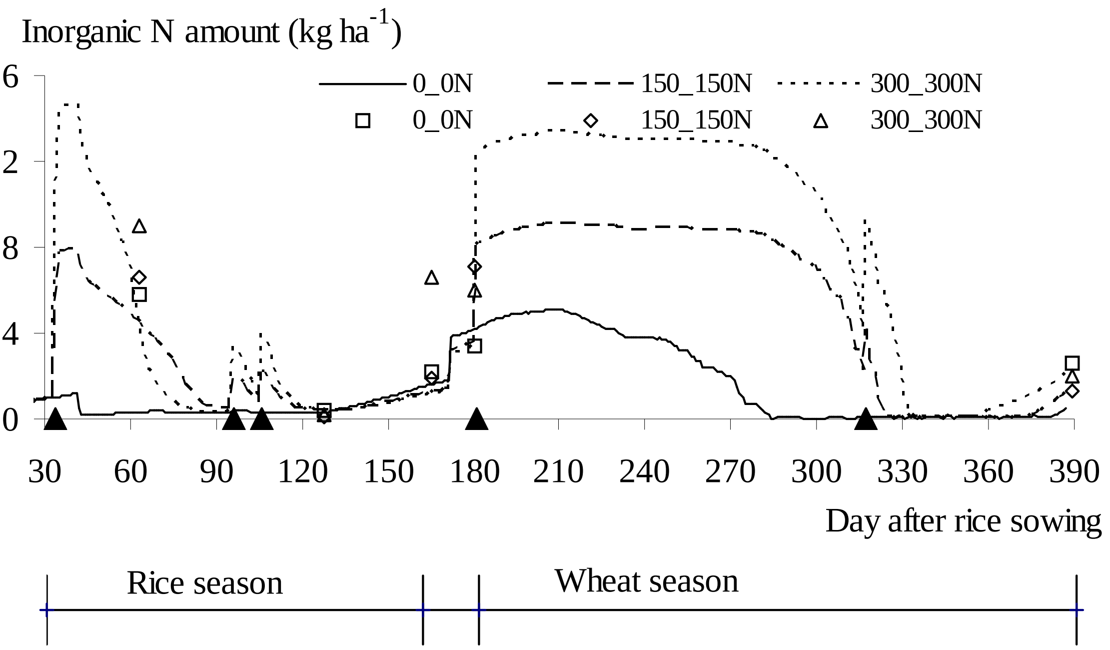


Figure 6.8 *Simulated (lines) and measured (symbols) soil inorganic N amount in top 10 mm soil layer in the rice-wheat sequence at different N rates in 2002-2003. On day 180, measured values were from the samples collected before N application. Triangles on the horizontal axis indicate N fertilizer applications. (N-doses given in Table 6.2).*

Soil inorganic N content varied considerably in the course of the crop growth seasons and among N rates, with peaks following fertilizer application (Fig. 6.8). Simulated values follow the pattern of the measurements, with similar absolute values, indicating that the model satisfactorily reproduces the dynamics of soil inorganic N.

Net mineralization is defined as calculated total mineralization minus immobilization. Simulated values of net N mineralization were more or less stable in the course of the rice growing season, decreased following wheat sowing and during the winter period and then again increased during the spring and summer periods (Fig. 6.9(a)), reflecting the annual variation in temperature and soil water content. Under the rice crop, net N mineralization increased following fertilizer application, while under the wheat crop, there was no indication of fertilizer-induced enhanced mineralization following the first N dose, and a minor effect following the second N dose, suggesting different responses of net N mineralization to N fertilizer between anaerobic and aerobic conditions. Soil water content was at saturation during the flooded rice season (Fig. 6.9(b)), and subsequently decreased till field capacity in the wheat season during which it varied with rainfall. There are minor variations in soil water content among N rates at the last growth stages of both crops.

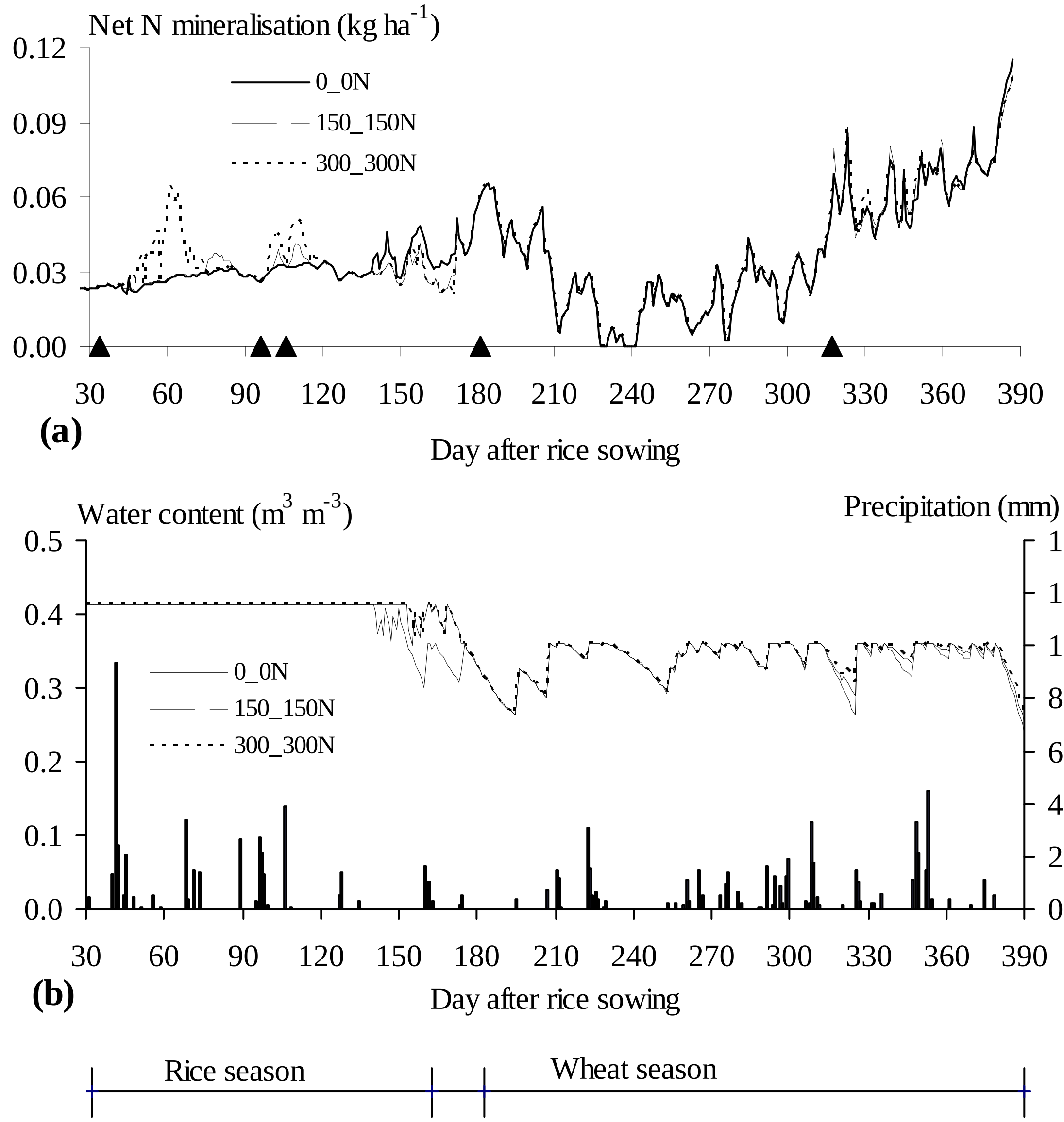


Figure 6.9 *Simulated dynamics of net N mineralization in top 10 mm soil layer (a) and soil water content in the rice-wheat sequence at different N rates (b) in 2002-2003. Triangles on the horizontal axis indicate N fertilizer applications. (For N-doses, see Table 6.2).*

6.4 Discussion and conclusions

RIWER allows continuous simulation of soil conditions, following initialization at the start of a simulation session, including (a number of) rice-wheat crop sequences, user-specified in terms of crop management, such as sowing and transplanting dates, crop density, and N management, *i.e.* dates, rates, types and application methods. For anaerobic soil conditions during the submerged rice season, we adapted the water module PADDY, and for aerobic soil conditions, we adapted and linked DRSAHE to the inter-crop (fallow) period and wheat season. The SOM module was adapted by including nitrification and denitrification, to simulate N mineralization under both aerobic and anaerobic conditions.

Within RIWER, the adapted SOM is linked to the rice model ORYZA2000, replacing the original simple description of crop-available N, *i.e.* set to the sum of a constant daily indigenous soil N supply rate and a maximum recovery of applied fertilizer N, defined as a function of crop development stage at application (Bouman *et al.*, 2001). In reality, indigenous soil N supply can vary substantially in the course of the growing season (Dobermann *et al.*, 2003a, b; Thiyagarajan *et al.*, 1997). The recovery of fertilizer N depends not only on the time of application, but also on management (method of application) and environmental conditions that affect volatilization and leaching losses. The incorporated SOM module led to improved results for simulated crop N-dynamics, compared to a previous study using ORYZA2000 (Jing *et al.*, 2007).

For proper evaluation of RIWER, (a) detailed experimental data set(s) are required, including information on aboveground and belowground processes. In our experiment, detailed information was available only for aboveground characteristics (crop biomass production and crop N uptake). RIWER performs well in simulating total aboveground biomass and N uptake, as assessed through graphical comparison and goodness-of-fit parameters of the (independent) validation set. In our experiment, only limited information was available on the dynamics of soil inorganic N, which RIWER satisfactorily reproduced. The large variation in net N mineralization during the wheat season was due to variations in temperature and soil water content which are major factors affecting N mineralization (Wang *et al.*, 2003b), as illustrated by the reduction in net N mineralization following sowing of wheat, associated with decreases in temperature.

The differential responses of net mineralization to N fertilizer between the rice and wheat seasons are the result of differences in soil inorganic N content in the non-fertilized situation. In rice, soil inorganic N content is low without fertilizer application, due to the low mineralization under flooded conditions (Fig. 6.8), while during the fallow period, soil inorganic N content increases to a relative high level before the first N application to wheat, which then declines until N fertilizer is applied for the second time, resulting in a slight positive response of net N mineralization.

N fertilizer significantly stimulated leaf development in both rice (Jing *et al.*, 2007) and wheat (Lawless *et al.*, 2005), leading to differences in evapotranspiration among N rates, and thus to differences in soil water dynamics (Fig. 6.9 (b)).

RIWER has considerable potential for evaluation of crop and soil management practices in rice-wheat cropping systems, as illustrated by assessment of its performance in terms of simulated aboveground biomass, N uptake and net N mineralization. Hence, RIWER provides a promising and operational framework to support the development of more sustainable RW systems, combining environmentally-friendly production methods and high yields. However, to increase confidence in model results, more extensive testing is needed, especially with respect to soil processes. This will require dedicated field experiments in which the proper processes are monitored and measured.

7. General discussion

Global food production needs to increase dramatically to feed a growing population in the next decades (Cassman, 1999; FAO, 2003; Khush, 2005). Especially in Asia the food demand will be high because it is home to half of the global population, while increasing living standards cause a shift from the traditional cereal-based diets towards more affluent animal-based diets (Pingali, 2007; Smil, 2004a). This has given rise to a discussion about the real increase in demand for cereals (Smil, 2004b), but it is evident that cereal producers must increase yields without additional or even with less arable land and less water, due to the competition for these resources from urbanization and other sectors (Brockherhoff, 2000; Chen, 2007; Lu *et al.*, 2007a).

Intensive cropping systems, such as double- or triple-rice and rice-wheat (RW) rotations are common throughout Asia, including China. Both rice and wheat are grown throughout China and RW rotations occupy 10% of its arable land (Huke and Huke, 1992). High nutrient inputs have contributed to increased cereal yields in the last fifty years (Goudriaan *et al.*, 2001), but increases in yields have leveled off or even ceased in recent years despite high(er) fertilizer inputs (Ladha *et al.*, 2003). These (very) high nutrient inputs are associated with environmental problems such as pollution of surface- and groundwater and emissions of greenhouse gases (Kumazawa, 2002; Li *et al.*, 2000; Liu *et al.*, 2003; Tong *et al.*, 2003; Zhang *et al.*, 1996; Zhu *et al.*, 2000).

Food security and safety remain important objectives in the coming decades (Roetter and Van Keulen, 2007), but the need for more sustainable and environmentally friendly production methods has been added to the policy and research agenda. Agricultural production systems, combining high resource use efficiencies and high yields will be increasingly important to meet the challenges that the future provides.

In this study, both experimental and modelling approaches were used to increase understanding of crop growth and nitrogen dynamics in irrigated RW systems with the aim to contribute to the improvement of N management in these systems as a basis for the design of high-yielding RW systems, characterized by high N use efficiencies (NUE).

7.1 Options to increase yield and quality

7.1.1 Yield

Yield is determined by the interaction of genotypic (G) and environmental (E) factors which can be modified by management (M), *e.g.* choice of genotype, and soil and crop management. The relative importance of each of these factors in specific situations is as yet difficult to predict. In the multi-location experiments described in Chapter 2, 10% of the observed variation in rice yields could be explained by genetic differences, while 80% of the yield variation was caused by environmental differences among locations. Therefore, the performance of genotypes should be evaluated in the environmental context in which they are expected to function. For example, *Indica* genotypes usually produce higher yields in the tropics than *Japonica* genotypes, while under cool sub-tropical conditions *Japonica* performs better due to morphological adaptation (Glaszmann, 1987; Morishima and Oka, 1981). Key characteristics of high-yielding genotypes are a high biomass production under the prevailing environmental conditions, combined with a favorable harvest index (Ying *et al.*, 1998a; Chapter 2).

Multiple environmental factors affect crop yields, such as soil properties (*e.g.* soil organic matter content and water holding capacity) and climatic characteristics (radiation and temperature). In Chapter 3, we used a modelling approach to separate and compare the contribution of three environmental factors (soil N, radiation and temperature) to yield variation. In high-yielding RW systems, the effect of indigenous soil N supply on yield variation can be modified by N management, *i.e.* the effect of indigenous soil N supply declines with increasing N fertilizer rate. Temperature substantially contributes to the observed yield variation in rice due to its effect on phenological development rate and thus growth duration (Yin *et al.*, 1997), and on spikelet sterility (Lee, 2001; Prasad *et al.*, 2006). Mean temperature during ripening had a significant effect on yield according to an optimum-type response, *i.e.* yields are lower when temperatures deviate from a genotype-specific optimum. Adaptation of sowing/transplanting dates so that temperatures during grain filling would be more favorable, could increase rice yields with 10% in the current RW areas of China (Huang *et al.*, 1998). However, such a modification in cropping calendar is not always feasible in RW systems, because of the short transition period between both crops.

In the RW experiment (Chapter 5), total system yield was comparable to those obtained by farmers and in other experiments in Jiangsu, *i.e.* about 12-13,500 kg ha^{-1} (Table 7.1), with an average rice yield of 9,000 kg ha^{-1} and a wheat yield of 3,000 kg ha^{-1}. Simulated yield potentials of rice are 10-11,000 kg ha^{-1} (Chapter 4), while wheat yields of 7,000 kg ha^{-1} have been recorded in Jiangsu (Table 7.2). These data suggest that the yield potentials of RW systems may be around 17,000 kg ha^{-1}, which could be realized through improvements in current management.

Table 7.1 Mean yield of rice and wheat in RW systems in Jiangsu Province, China.

Sources	Yield (kg ha^{-1})		
	Rice	Wheat	Total
Provincial mean (China statistical year book, 2004)	8301	4165	12466
Short term experiment (Wang *et al*., 2003a)	7925	5567	13492
Long term experiment (Zhuang *et al*., 1999)	7301	4933	12234

Table7. 2 Wheat yields in experiments at different sites in Jiangsu, China.

Genotype	Yield (kg ha^{-1})	N Fertilizer (kg ha^{-1})	Site	Source
Yangmai10	7043	240	Yangzhou	Gu *et al*., 2005
Jinan17	7628	290	Yandou	Wu *et al*., 2002
Jinan17	7809	320	Rugao	Ge *et al*., 2003
Ningmai9	7229	240	Kunshan	Lu *et al*., 2007b
Ningmai9	7351	260	Baoying	Zhou *et al*., 2005
Huaimai18	6960	225	Xuzhou	Shen *et al*., 2004

7.1.2 Quality

Quality of rice grains is not easily defined, as it depends on consumer preferences (Unnevehr, 1986) and the intended end use of the grain. There are many indicators of rice grain quality, including physical and chemical indicators (cf. Fitzgerald and Reinke, 2006), and many factors affect grain quality, such as growing conditions, harvesting stage, the nature of the milling process and storage conditions. In general, the contents of the main components of rice grains, *i.e.* protein and starch, and their ratios are related to the quality of rice. Protein content is a nutritional indicator, and the content of amylose, the soluble component of starch, is especially important for the cooking characteristics and thus directly related to the preference of consumers (Juliano, 1985; Lii *et al*., 1996). Generally, *Japonica* rice with a relatively low amylose content is preferred in Taiwan, rice with a low to intermediate amylose content in Korea, while consumers in the Philippines prefer soft rice with an intermediate amylose content (Loewer *et al*., 2003). In our multi-location experiment, about 70% of the variation in amylose content in rice could be explained by genotypic differences (Chapter 2). Hence, any production of rice with a targeted amylose content needs to take these genetic differences into account. Temperature is the major environmental factor affecting amylose content, *i.e.* low temperatures during ripening lead to higher amylose contents (Chapter 2). In the subtropics, where temperature varies more than in the tropics, sowing date could be adapted to influence amylose content. However, as indicated in the previous section, the fallow period in RW systems may be too short to allow flexibility in sowing and harvesting dates. N fertilizer management significantly affects protein content of rice grains (Borrell *et al*., 1999; Perez *et al*., 1996), but hardly their amylose content (Yang *et al*., 2007).

In contrast to rice quality, wheat quality is clearly defined according to its end use, *i.e.* the processing into different food products (Bekes *et al*., 2004; Wrigley and Bekes, 2004). Protein content is the most important indicator for wheat grain quality (Barneix, 2007). Generally, wheat for producing biscuits requires low protein contents, while bread wheat requires a relative high protein content. In addition to low N fertilizer inputs, other factors such as low temperature during grain filling and limited water supply may lead to lower protein contents in wheat (Dupont *et al*., 2006; Oweis *et al*., 1999). Recently, zones in China have been identified for the production of wheat with well-defined quality characteristics (He *et al*., 2002). Most RW areas are in the production zone that is suitable for producing wheat with low to median protein contents. Limiting N fertilizer input in wheat may reduce its protein content, but this may go at the expense of yield. In addition to the zonation for well-defined wheat quality, alternative management regimes for RW systems should be developed to obtain wheat with low protein content without large yield losses.

7.2 Options to increase resource use efficiency

Resources refer to the production factors that a crop uses in realising growth and production, such as land, nutrients, water and radiation. Resource use efficiencies are important indicators to assess the performance of agricultural systems (Giller *et al*., 2006). In this study, I mainly focused on nitrogen use efficiency (NUE) in relation to the availability of other resources. Generally, three indicators are used to evaluate NUE (Table 7.3), *i.e.* Internal N Use Efficiency (INUE, kg grain per kg N-uptake), Agronomic Efficiency (AE, kg grain per kg fertilizer N) and fertilizer N Recovery (RE, kg N-uptake per kg fertilizer N).

Table7.3 Indicators of nitrogen use efficiency and their definitions.

Indicator	Definition
INUE (Internal N Use Efficiency, kg kg^{-1})	Grain yield obtained from a unit of N absorbed in plant
AE (Agronomic Efficiency, kg kg^{-1})	The incremental increase in grain yield that results from a unit of applied N
RE (Fertilizer N Recovery, %)	The increment of crop N accumulation that results from N application divided by total applied fertilizer N

Based on the experiments carried out in this study, environmental factors contributed more to the variation in N uptake than differences in genotype. Among environmental factors, indigenous soil N supply affected N uptake more than weather (Chapter 3). Therefore, in formulating fertilizer recommendations for RW systems should take into account the amount of N that is supplied from natural sources, such as soil organic matter. Until recently, this N supply was often not explicitly taken into account in N recommendations and N management in practice. The Mega projects ‘Reversing Trends of Declining Productivity’ (RTDP) and ‘Reaching Toward Optimal Productivity’ (RTOP) of IRRI’s Irrigated Rice Research Consortium have resulted in development of the so-called 'Site-Specific Nutrient Management (SSNM)' technology for irrigated rice, in which NPK fertilizer applications are based on explicit estimation of indigenous soil nutrient supply, yield targets and estimated crop nutrient demands (Buresh *et al.*, 2005; Dobermann *et al.*, 2004). The principles of SSNM are based on matching N supply to crop N demand, which is similar to the concepts used in the models for simulating crop N uptake in this study (Chapter 6). In SSNM, indigenous soil N supply is estimated from crop N uptake in N omission plots. Indigenous soil N supply strongly varies across Asia associated with differences in weather and in soil conditions, partly as a result of past cropping history (Dobermann *et al.*, 2003a, b). A geographic database with up-to-date soil information (soil type, organic matter content, *etc*.) and estimated indigenous soil N supply could be developed to support local authorities in charge of soil resources management. On the basis of such information location-specific N fertilizer recommendations could be formulated, better matching the pattern of N supply to crop demand. When indigenous soil N supply can not meet crop demand, an appropriate amount of N fertilizer needs to be applied at the appropriate moment. However, this is not easy to realize in practice without a visual or other simple operational indicator for farmers. Within the framework of SSNM, crop N demand is derived from leaf N status, which can be monitored with a low-cost leaf colour chart (LCC) or a more costly chlorophyll meter (SPAD) (Balasubramanian *et* *al*., 1999; Witt *et al*., 2005). Using such tools, critical leaf N levels can be determined below which N fertilizer should be applied. SSNM appears an appropriate technology to reduce fertilizer use and save on costs in rice production, but it needs continuous crop monitoring and associated new skills of farmers (Wang *et al*., 2007). Models may contribute to further finetune SSNM by estimating daily crop N demand, daily indigenous soil N supply, and N fertilizer requirements to realize a target yield from location-specific soil and climate conditions. Moreover, the model can be applied to formulate fertilizer management scenarios, comprising different application rates and times of application to identify the most favourable regime, provided N dynamics in both crops and soil can be simulated accurately, as well as the response in terms of crop growth and production. When the model performs satisfactorily, it could be used in conjuction with the actual fertilizer regime, which could make crop monitoring as part of SSNM obsolete. The promising performance of SSNM in many rice-based systems (Dobermann *et al*., 2004) suggests that similar strategies could also work in wheat.

Crop performance of rice is strongly influenced by N uptake in the crop (Cassman *et al*., 1998). INUE varies among genotypes (Singh *et al*., 1998), which is confirmed in this study (Chapter 3). Rice genotypes with higher harvest indices and larger sink size show higher values of INUE (Chapters 2 and 3; Mae *et al*., 2006; Van Keulen, 1982), which results in efficient translocation of dry matter and nutrients to the grains during grain filling. Using SSNM in rice, INUE improved from the current 30-35 kg grain kg^{-1} N in farmers' practice to around 50 kg grain kg^{-1} N, while AE increased from 4 kg kg^{-1} to more than 10 kg kg^{-1} (Peng *et al*., 2006). My study shows that on the basis of model simulations and taking into account indigenous soil N supply INUE could be further increased to around 60 kg grain kg^{-1} N (Chapter 4). This is similar to the maximum INUE (68 kg grain kg^{-1} N) estimated in the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model (Janssen *et al*., 1990) with a balanced supply of N, P and K (Witt *et al*., 1999).

Excessive N applications are the major cause of N losses in current irrigated rice-based cropping systems in China. Especially at the beginning of both the rice and wheat season farmers apply large quantities of N fertilizer (usually more than 60% of the total applied N), when only a small part of the N can be absorbed by the crop (Glass, 2003). Major N loss processes include volatilization, denitrification, surface runoff and leaching (Raun and Johnson, 1999; Reddy and Patrick, 1986), all of which are associated with soil water dynamics that drive transport and transformations of N in the soil. Facing the anticipated increase in water scarcity (CA, 2007; FAO, 2003), water saving technologies are being developed, especially for irrigated rice, because of the high water input in these systems. For example, Alternating Drying-Wetting irrigation (AWD) which reduces irrigation water inputs by 15-20% compared to traditional flooded rice, without affecting yield (Belder *et al.*, 2004). The alternate drying-wetting of the soil as part of AWD, on the one hand stimulates organic matter decomposition, leading to a temporary increase in inorganic soil nitrogen, increasing denitrification and hence N losses (Qiu and McComb, 1996; Reddy *et al.*, 1989). On the other hand, AWD irrigation may lead to increased N uptake by the subsequent wheat crop (Chapter 5). One of the possible reasons is the higher root biomass of rice under AWD irrigation (Yang *et al.*, 2004), resulting in higher N mineralization from residues. Further research is required to investigate this hypothesis.

The interactions between water regime, crop N uptake and N losses in irrigated RW systems are complex, and models are useful tools for quantification of such interactions to increase insight in these complex processes. Crop growth models have been applied in exploring options to increase resource use efficiencies in single rice or wheat crops (Jones *et al.*, 2003; Keating *et al.*, 2003; Van Ittersum *et al.*, 2003). However, during the fallow period between the rice and wheat seasons in RW systems, N losses may increase due to the alternation of aerobic and anaerobic soil conditions. N dynamics during fallow periods in RW systems need to be more accurately quantified (Ladha *et al.*, 2000b; Zheng *et al.*, 2000) as a basis for modification of their management towards more environmentally-friendly production practices. Only models that continuously simulate N dynamics under both aerobic and anaerobic soil conditions are able to contribute to this quest. Few soil organic matter models exist that are able to simulate anaerobic soil conditions as in irrigated rice (Shibu *et al.*, 2006), which hampers quantification of N dynamics during the alternating dry-wet soil conditions in RW systems. In this study, the RIWER model (Chapter 6) aims at capturing those processes that are relevant during the alternation of aerobic conditions in the wheat season and anaerobic conditions in the rice season. RIWER offers an operational and promising tool for designing sustainable RW systems, that combine environmentally-friendly production methods and high yields.

7.3 Approaches of modelling and experimentation

Crop models mimic the growth and development of crops. Crop models are based on existing insights in the underlying chemistry, physics, physiology and ecology of crops. Information on weather, soil, and crop management is combined and processed to predict crop performance and resource use efficiency. Often, two methods are used to evaluate model results, *i.e.* through graphical comparison of simulated and observed values, and through statistical testing, such as a *t-test* and *RMSE,* also used in this study to estimate the quantitative accuracy of model results. There are no absolute criteria to classify a model as “good” or “bad”. Strictly speaking, models cannot be validated; only invalidation is possible on the basis of empirical evidence. However, repeated and well-documented comparisons between predicted and observed values increase the confidence in the suitability of a model for a specific purpose (Bouman and Van Laar, 2006). Alternatively, models are useful tools to identify and gain insight in complex processes, and to facilitate the design of management regimes for realizing specific production objectives. This study successfully identified the relative importance of environmental factors, such as indigenous soil N supply, temperature and radiation for rice yield and N uptake (Chapter 3). Additionally, various scenarios were analyzed to examine the scope for improvements in N fertilizer management aiming at high yields combined with high N use efficiency, taking into account indigenous soil N supply (Chapter 4).

Model-based approaches could further support the quest for new water-saving and N management technologies, by evaluating alternative management packages before they are tested or disseminated in practice. An advantage of using model approaches is that alternative N management practices can be designed and evaluated, that match new water management regimes. RIWER, in combination with appropriately designed experiments could be used to evaluate such alternative technologies.

To create confidence in models as effective tools, existing models have to be calibrated and validated based on crop genetic characteristics and location-specific conditions before they can be successfully applied. This requires independent detailed data sets that are often not available or accessible for potential model end users such as farmers and policy makers. This may be one of the major reasons that models are mainly applied by researchers. Model development still has to go a long way before models are sufficiently generic, trustworthy and user-friendly to be applicable by a wide range of end users (Carberry *et al*., 2002; Dimes *et al*., 2002; Reddy *et al*., 2005; Stone and Hochman, 2004).

7.4 Concluding remarks

In this study, RIWER could only be evaluated with respect to total biomass, N uptake and soil inorganic N content. Testing the performance of the denitrifcation module and SOM module under anaerobic conditions needs additional work, which is hampered by the availability of suitable data sets to test the model. After successful evaluation of RIWER, it could be used to support exploration of options to improve the efficiency of other resources, such as water; and to better quantify N losses in RW systems, *etc*. The long-term effects of crop residue management, manure and chemical fertilizer applications, as well as soil management, such as puddling in rice and conservation tillage in wheat on yield and soil fertility can be analysed in model scenarios.

With improvements in food security and livelihoods in China and elsewhere in Asia, there will be increased demand for rice with well-defined quality characteristics. In addition to genotype, environment and crop management (*e.g.* sowing date), N and water management significantly affect grain quality. Possibly, a sub-module on rice grain quality formation can be developed and linked to ORYZA2000, enabling prediction of quality characteristics of rice grain. Similarly, a sub-module on the formation of protein could be developed for SWHEAT, enabling evaluation of different N management regimes on wheat grain quality.

Despite the promising role of crop growth models such as RIWER in design, development and testing of new technologies, such models are not (yet) able to capture important processes in RW systems, for example related to specific growth-limiting (such as phosphorus and potassium) and growth-reducing factors (pests, diseases and weeds). It is a challenge to improve our insights in such processes to enable their incorporation in comprehensive robust models, on the basis of which new integrated management practices can be developed aimed at high-yielding and resource-use efficient RW systems with targeted product quality.

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Summary

Globally, cereal producers need to increase production per unit area to respond to the increasing food demand for a growing population, in the face of decreasing availability of arable land due to competing claims originating from urban and industrial development. At the same time, high-yielding irrigated rice-based cropping systems in China and elsewhere in Asia, are increasingly being associated with environmental problems and low resource use efficiencies. Nitrogen (N) losses to the environment may be especially high where aerobic and anaerobic soil conditions alternate, such as in rice-wheat (RW) rotations. In the coming decades, development of sustainable, environmentally-friendly production systems, yielding well-defined quality products, needs major attention in research and policy.

The objective of this study is to contribute to better understanding of the productivity and nitrogen dynamics of irrigated RW systems, as a basis for improved N management in these systems as a component in the design of RW systems that combine high yields of the desired quality with high N use efficiency. To achieve this objective, I have combined experimental and modelling approaches. Field experiments with different rice genotypes were carried out in multiple environments, as well as RW rotation trials under different N and water management regimes. The modelling activities in the study included application of the rice growth model ORYZA2000 and development of a rice-wheat rotation model (RIWER), on the basis of existing simulation modules.

In Chapter 2, the relative importance of genotypic characteristics and environmental conditions on yield and quality of rice was examined and relationships between on the one hand weather conditions (temperature, radiation) and on the other hand yield and grain quality were quantified. The concept of the photothermal quotient as an explanatory characteristic for yield variability was tested with data from multi-location experiments across tropical and sub-tropical areas of Asia. Environmental characteristics explained 80% of the observed variation in grain yield and 66% of the variation in harvest index (HI). Low yields at tropical locations were related to low radiation interception, resulting from fast phenological development during the vegetative phase, and to low HI, resulting from restricted grain formation during the reproductive phase. Using a second order polynomial equation, average temperature during ripening (ATR) satisfactorily explained the variation in yield and HI among genotypes. Genotype explained 72% of the variation in rice grain amylose content, while grain amylose content increased linearly with decreasing ATR.

Chapter 3 aimed at identifying the relative importance of environmental factors (indigenous soil N supply, temperature, radiation) on rice yield, N uptake and internal

nitrogen use efficiency (INUE, grain yield per unit total aboveground crop N uptake), using the crop growth model ORYZA2000 that was evaluated on the basis of the experimental data of Chapter 2. Indigenous soil N supply had a stronger effect on yield and INUE than weather conditions at low N-fertilizer application rates, but its relative effect declined at high N-fertilizer rates. At both, low and high N-fertilizer application rates, indigenous soil N supply had a stronger effect on total crop N uptake than weather conditions. Temperature contributed more than radiation to the variation in yield, N uptake and INUE. These results indicate that N fertilizer management should take into account (site-specific) indigenous soil N supply, while temperature is the primary factor in selection of genotypes and identification of (optimum) sowing dates in rice production.

Chapter 4 combines field experimentation with simulation modelling to explore N fertilizer management strategies to realize high yields, while increasing N use efficiency. Highest yields were obtained with N application rates of 150-200 kg ha^{-1}, taking into account an indigenous soil N supply of 0.6-0.9 kg ha^{-1} d^{-1}. High values for N fertilizer recovery (53-56%) and agronomic N use efficiency (20-30 kg grain kg^{-1} N applied) were obtained with split application of the N fertilizer, with equal doses at transplanting, panicle initiation and booting. Increasing the number of splits to six did not further increase yield or improve any of the N use efficiency parameters.

Chapter 5 analyses N dynamics and N response in a RW experiment under different N and water management regimes. Nitrogen uptake in both, rice and wheat increased with increasing N rates, while agronomic nitrogen use efficiency decreased at N application rates exceeding 150 kg ha^{-1}. Carry-over of residual N from rice to the subsequent wheat crop was limited, consistent with the low soil nitrate concentrations after rice harvest. Total soil N content hardly changed in the course of the experiment, reflecting storage of most of the N in organic matter. There were no significant yield differences between different water management regimes, *i.e.* conventional flooding or intermittent irrigation during the rice season, but apparent N recovery was higher under intermittent irrigation. In one season, intermittent irrigation resulted in higher N uptake in the subsequent wheat crop, but not in higher yield.

The development of a rice-wheat rotation model (RIWER) is described in Chapter 6. The model is based on integration of existing crop and soil modules and adaptation to both aerobic and anaerobic conditions. RIWER simulates soil processes continuously, following initialization of soil conditions once at the start of a simulation experiment, while crop management, such as sowing/transplanting dates, plant density and N fertilizer regime are user-defined before each cropping season. Based on partial evaluation, RIWER showed satisfactory performance in terms of crop biomass, crop N uptake and soil inorganic N content, while simulated values of soil water content and

net N mineralisation under different N rates are plausible. Comprehensive testing of the model was not possible, due to limited availability of suitable empirical data, but the simulation results give confidence that RIWER is a good starting point for further analyses of RW systems.

The thesis concludes with identification of options to improve yields and resource use efficiencies in irrigated RW systems. Flexible sowing dates and fertilizer management aiming at synchronization of N supply and crop demand could lead to higher crop yields and enhanced N use efficiency in rice-based systems. Repeated transitions in RW systems between aerobic soil conditions for wheat and anaerobic conditions for rice require approaches combining experimentation and modelling in designing new integrated management systems aiming at high-yielding, resource-use efficient RW systems with a targeted product quality.

Samenvatting

Wereldwijd moeten graanproducenten de productie per eenheid landoppervlak verhogen om te kunnen blijven voldoen aan de toenemende vraag naar voedsel voor een groeiende bevolking, terwijl de beschikbaarheid van akkerbouwland afneemt door verstedelijking en industrialisatie. Tegelijkertijd neemt de kritiek op intensieve gewassystemen met geïrrigeerde rijst in China en elders in Azië toe in verband met milieuproblemen en lage benuttingsefficiënties van hulpbronnen. Stikstof(N)verliezen naar het milieu zijn in het bijzonder hoog in situaties waar aerobe en anaerobe bodemcondities elkaar afwisselen, zoals in rijst-tarwe- (RW-) rotaties. In de komende decennia vergt de ontwikkeling van duurzame en milieuvriendelijke productie-systemen, waarin welomschreven kwaliteitsproducten worden geproduceerd, nadrukkelijk de aandacht van het onderzoek en de politiek.

Het doel van deze studie is om bij te dragen aan een beter begrip van de productiviteit en stikstofdynamiek van geïrrigeerde RW-systemen, als basis voor het ontwerpen van systemen met een verbeterd N-beheer, gericht op hoge opbrengsten van de gewenste kwaliteit en met een hoge N-benuttingsefficiëntie. Om dit doel te bereiken, heb ik verschillende experimentele en modelmatige benaderingen gecombineerd. Naast veldproeven met verschillende rijstrassen op meerdere locaties, zijn er RW-rotatieproeven uitgevoerd met verschillend N- en watermanagement. Bij de modelmatige benaderingen is aan de ene kant het gewasgroeimodel ORYZA2000 toegepast, en aan de andere kant een rijst-tarwe-rotatiemodel (RIWER) ontwikkeld, op basis van bestaande simulatiemodules.

In Hoofdstuk 2 is het relatieve belang van raskenmerken en omgevings-omstandigheden op de opbrengst en kwaliteit van rijst onderzocht, en zijn de relaties tussen enerzijds weersomstandigheden (temperatuur en straling) en anderzijds opbrengst en korrelkwaliteit gekwantificeerd. Het concept van het fotothermische quotiënt, de verhouding tussen straling en temperatuur, als verklarende variabele voor verschillen in opbrengst, is getest met gegevens van multi-locatie-experimenten in tropisch en subtropisch Azië. Omgevingskenmerken verklaarden 80% van de waargenomen variatie in korrelopbrengst en 66% van de variatie in oogstindex (HI). Lage opbrengsten in tropische locaties konden worden verklaard uit een lage stralingsonderschepping als gevolg van een korte vegetatieve fase door een snelle fenologische ontwikkeling, en een lage HI door een beperkte korrelzetting gedurende de generatieve fase. Met behulp van een tweede orde polynoom kon de variatie in opbrengst en HI goed verklaard worden uit de gemiddelde temperatuur gedurende de korrelvulling (ATR). Raskenmerken verklaarden 72% van de variatie in amylosegehalte in de graankorrels, en het amylosegehalte nam rechtlijnig toe met afnemende ATR.

Hoofdstuk 3 is gericht op het identificeren van het relatieve belang van omgevingsfactoren (N-beschikbaarheid uit natuurlijke bronnen, temperatuur en straling) op de opbrengst, N-opname en interne N-benuttingsefficiëntie (INUE, korrelopbrengst per eenheid N-opname in de bovengrondse biomassa) van rijst. Hiervoor wordt gebruik gemaakt van het gewasgroeimodel ORYZA2000 dat werd getoetst met de experimentele gegevens beschreven in Hoofdstuk 2. N-beschikbaarheid uit natuurlijke bronnen had een sterker effect op de opbrengst en op INUE dan de weersomstandigheden bij lage N-bemestingsniveaus, maar dit relatieve effect nam af bij hoge N-bemestingsniveaus. Zowel bij lage als hoge N-bemestingsniveaus had de N-beschikbaarheid uit natuurlijke bronnen een sterker effect op de totale N-opname in het gewas dan de weersomstandigheden. Temperatuur droeg meer bij aan de variatie in opbrengst, N-opname en INUE dan straling. Deze resultaten wijzen erop dat bij het N-management rekening moet worden gehouden met de (plaats-specifieke) N-beschikbaarheid uit natuurlijke bronnen, terwijl temperatuur de belangrijkste factor is bij rassenkeuze en keuze van (optimale) zaaidata voor de productie van rijst.

Hoofdstuk 4 combineert veldproeven met simulatieexperimenten bij het verkennen van N-bemestingsstrategieën, gericht op het combineren van hoge korrelopbrengsten met hoge N-benuttingsefficiënties. De hoogste opbrengsten werden behaald bij N-giften van 150-200 kg ha^{-1}, waarbij de N-beschikbaarheid uit natuurlijke bronnen op 0.6-0.9 kg ha^{-1} d^{-1} werd gezet. Hoge waarden voor het N-uitbatingspercentage (“recovery”) en de agronomische N-benuttingsefficiëntie (20-30 kg korrel kg^{-1} toegediende N) werden behaald bij een gedeelde toediening van N, met gelijke giften bij het overplanten, en bij het begin en het eind van de pluimvorming. Verhoging tot zes deelgiften leidde niet tot opbrengstverhoging en verbetering van de N-benuttingsefficiëntie.

Hoofdstuk 5 analyseert de N-dynamiek en de reactie op N-toediening in een meerjarige RW-proef onder verschillende N- and water-managementregimes. De opname van stikstof in zowel rijst als tarwe nam toe met hogere N-giften, terwijl de agronomische N-benuttingsefficiëntie afnam bij N-giften boven 150 kg ha^{-1}. De nawerking van N toegediend aan rijst op het volgende tarwegewas was beperkt, zoals verwacht kon worden, gezien de lage N-concentraties in de bodem na de oogst van rijst. Het gehalte aan N-totaal in de bodem varieerde heel weinig in de loop van de proef, omdat het merendeel van de N in de bodem in organische stof is vastgelegd. Er waren geen grote opbrengstverschillen in rijst tussen de twee toegepaste waterregimes, continue bevloeiing en afwisselend bevloeid-niet-bevloeide omstandigheden, maar het schijnbare uitbatingspercentage was hoger onder laatstgenoemde omstandigheden. In één van de twee jaren resulteerde de afwisselend bevloeid-niet-bevloeide behandeling in een hogere N-opname in het volgende tarwegewas, maar niet in een hogere korrelopbrengst.

De ontwikkeling van het rijst-tarwe-model (RIWER) is beschreven in Hoofdstuk 6. Het model is gebaseerd op integratie van bestaande modules voor simulatie van gewas en bodem en aanpassing van deze modules voor zowel aerobe als anaerobe omstandigheden. Na initialisatie van de bodemcondities simuleert RIWER de bodemprocessen continue, terwijl gewas-specifieke informatie zoals tijdstip van zaaien/overplanten, plant(zaai)dichtheid en N-bemestingsregime vóór elk groeiseizoen door de modelgebruiker moet worden gespecificeerd. RIWER simuleerde de dynamiek van de bovengrondse drogestofproductie van het gewas, de N-opname in het gewas en het anorganisch N-gehalte in de bodem op een bevredigende manier, terwijl het gesimuleerde watergehalte in de bodem en de netto N-mineralisatie, waarvoor geen gemeten waarden beschikbaar waren, plausibel lijken. Volledige toetsing van het model was onmogelijk vanwege het ontbreken van empirische gegevens, maar de simulatieresultaten geven vertrouwen dat RIWER een goede basis vormt voor de analyse van RW systemen.

De thesis besluit met identificatie van een aantal opties om de opbrengst en de benuttingsefficiëntie van hulpbronnen in geïrrigeerde RW systemen te verbeteren. Flexibele zaaidata en een bemestingsregime gericht op synchronisatie van het aanbod aan N en de behoefte van het gewas, kunnen leiden tot hogere gewasopbrengsten en verbeterde N-benuttingsefficiëntie in systemen met rijst. De specifieke karakteristieken van RW-systemen, met name de regelmatige overgangen tussen aërobe en anaërobe bodemomstandigheden, vragen om een combinatie van experimentele en modelbenaderingen om nieuwe geïntegreerde managementsystemen te ontwerpen, gericht op hoge opbrengsten van producten van een welomschreven kwaliteit en hoge gebruiksefficiënties van hulpbronnen (met name N en water).

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- Gene-plant-crop relations scale and complexity in plant systems research (2006)

International Symposia, Workshops and Conferences (6 credits)
- The 3rd international N conference (2004)
- The international conference on environmental modelling and simulation EMS2007 (2007)

Curriculum vitae

Qi JING was born in Xiao County, Anhui Province, P.R. China, on May 8th, 1975. He graduated from Nanjing Agricultural University (NAU), Nanjing, China, with a BSc degree in Horticultural Science in 1998. He continued his study as MSc student working on crop eco-physiology at NAU. After he received his MSc degree in 2001, he began to work as a teacher and researcher at NAU. In 2002, he became involved in the ‘Water-less rice’ project of Plant Research International (PRI). One year later, this project provided him the funding to enrol in a Sandwich Ph.D. programme at the C.T. de Wit graduate school for Production Ecology and Resource Conservation (PE&RC) of Wageningen University and Research Centre, the Netherlands. In 2005, he visited International Rice Research Institute (IRRI), the Philippines as a scholar for three months. His research area covers crop ecology and physiology, nutrient cycling, cropping systems and modelling. In his research area, he has published thirteen peer reviewed international papers and fifty national papers.

Selected peer-reviewed publications during Ph.D. study

2007

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