Water saving in lowland rice production: An experimental and modelling study

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Dit onderzoek is uitgevoerd binnen de onderzoekschool: Production Ecology and Resource Conservation.

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
prof. dr. ir. L. Speelman
in het openbaar te verdedigen
op woensdag 15 juni 2005
des namiddags te vier uur in de Aula

Paul Belder (2005)

Water saving in lowland rice production: An experimental and modelling study.
Belder, P. –[S.l.:s.n.]. Ill.
PhD thesis Wageningen University. –With ref.–
With summaries in English and Dutch
ISBN: 90-8504-224-0

Abstract

Belder, P., 2005. Water saving in lowland rice production: An experimental and modelling study. PhD thesis, Wageningen University, Wageningen, The Netherlands, 132 pp. with English and Dutch summaries.

Increasing demand for rice and decreasing water diversions to agriculture, urge for higher water productivity in rice production systems. One way to deal with this challenge is using water-saving regimes on field scale. The main objective of this study was to quantify the effects of water-saving regimes on water productivity, nitrogen use efficiency, and yield by a combined experimental and modeling approach. The role of subsurface hydrology was studied to assess the effects of water saving on the water balance.

Field experiments were conducted at three locations: Muñoz and Los Baños in the Philippines and Tuanlin in China. In experiments comparing alternate submerged-nonsubmerged (SNS) regimes — soils remained dry for several days before re-irrigation — with continuous submergence (CS), apparent nitrogen recovery and yield were at par and 15–18% of irrigation water could be saved thus leading to higher water productivity. Nitrogen supply plays a key role in enhancing water productivity because nitrogen promotes leaf area growth, biomass growth, and yield and reduces evaporative losses.

In most of our experiments, the groundwater table depth was shallow (<35 cm) so that hardly any water deficit occurred in SNS. When soil water tension in the root zone in water-saving regimes increased to 30–50 kPa, apparent nitrogen recoveries and yields were reduced.

In areas with acute water scarcity, the aerobic rice system is an option. In this system, rice is more or less grown as an upland crop. Irrigation water savings in experiments comparing aerobic rice with CS were nearly 40% but yields dropped with around 25%. In general, time and site-specific water management requires a detailed knowledge on crop growth and development, soil hydrological processes, and N cycling in the soil-plant system.

Keywords: Water balance, irrigation, water productivity, yield, apparent nitrogen recovery, nitrogen transformations, simulation.

Preface

In 1998 – during my M.Sc. study – I planned to conduct research on phosphorus deficiency in rice at Xieng Khouang province in Laos. Although the initial plan to work with the Dutch NGO ZOA was thwarted, I am still very thankful for the invitation of Luuk&Gerda and the country officer Bram van Grootheest. The Lao-IRRI project in the person of Bruce Linquist was involved in the planning of the research project and he kindly provided me the opportunity to do a similar experiment in de vicinity of the head office at Vientiane. Bruce taught me many things such as conducting a decent field experiment and reporting and communicating the findings to the public. I am also thankful for my other M.Sc. thesis supervisors Peter Leffelaar and Aad van Ast from the Theoretical Production Ecology group and Rien van Beusichem (Soil Fertility) for helping me to develop academic skills.

After completing my M.Sc. study in September 1999, I was looking for a research job that would enable me to work in Asia, more specifically China. Before the graduation, I met Prof. Huub Spiertz who informed me about a Ph.D. position on water $\times$ N interactions in rice in collaboration with IRRI and Chinese partners; I was immediately enthusiastic for this position. After I returned from a month of travelling in Asia, I met IRRI scientist Dr. Bas Bouman for an interview in Wageningen, a few hours before he would leave The Netherlands. With the beginning of a new century on January 1, 2000, I could start the study entitled 'water $\times$ N interactions and N economy in lowland rice under water-saving technologies' as a Ph.D. student in the Group of Crop and Weed Ecology (CWE) of Wageningen University and the CT de Wit Graduate School of Production Ecology and Resource Conservation (PE&RC).

This thesis would not have been as it is without the help and support of a great number of people. In the first place I want to thank both my supervisors Huub Spiertz and Bas Bouman for their intensive guidance during the entire project. We had numerous discussions often through email because it was very rare that we could meet all three at one place at the same time. Without your suggestions and help in all aspects of the research, this thesis would have been impossible to complete. Bas, thanks for all your fine arrangements for my stays at IRRI, the explanation of the model and bringing me into contact with other IRRI scientists. Also thanks for allowing me to participate in existing experiments and for the support to do my own field experiment. My gratitude also concerns Dr. T.P. Tuong who gave me the opportunity to work with the Chinese partners and for his supportive ideas. I am also thankful for the helpful discussions with Drs. Christian Witt, Shaobing Peng and Roland Buresh, senior IRRI staff, who shared their knowledge and experience with me

and gave me useful tips for conducting field experiments. I am indebted to the assistance of the Water Science people for arranging field trips, assistance in field experimentation and use of equipment, and other practical help. Lou, Lizzel, Annie, Liping, Romy, Ambi, June, Ernie, Lucio, Mary, Ruben, Ferdie, Doming and Lolit, thank you very much also for the nice working atmosphere. I am also indebted to the assistance of Romeo Visperas and his assistants and Dr. Shaobing Peng for managing the experiment in blocks K6-7 at IRRI. I also wish to thank Reynaldo Reyes and other assistants who did a great job in the field experiments at IRRI. My gratitude also concerns Violeta Bartholome of the Biometrics Unit at IRRI for suggestions for experimental set-up and data analysis and for provision of weather data by Zeny Pascual of the Climate Group. Also special thanks to Ike and Wency of the Soils group and the ASL staff for assistance and analysis of numerous soil, plant, and solution samples. *Maraming salamat po!*

After office hours, there were numerous spontaneous get-togethers (or ‘gimmicks’ as some call it), dinners, and sports activities. Especially the sports events organized by IRRI and the Saturday afternoon football on the UP campus made my stay more pleasant. I am grateful for the friendship of a great number of people from so many countries making my stay in Los Baños more pleasant and it would be impossible to name them all. Michiel, Stella, Mayank, Ruairi, Jiang Wen, Kofi, Gertjan, Pamela, Nikoleta, Claudia, Naveen, Rhulyx, Ten, Kazumi, Jaap, Frank, Mrs The and Thet, Sol, Lai, Pradeep, Parani, Olga, Mohsin, Tashi, Gay, Rainier, Unati, Neil, Manoj, Loc, Daniel, Janwillem, Youze, Tiago, Cecille, Arlene, Ben, Li Hua, Zahed, Zahir, Anselme, and Nicolas, thank you all for your friendship. Niranjan, I want to specially thank you for your kindness, spicy meals, adventures, and enormous sense of humor.

In general, I am thankful towards IRRI, especially to training center heads Paul Marcotte and Mark Bell, for giving me the opportunity to conduct a large part of my thesis work at IRRI, thereby providing me the facilities needed to do so.

The experiments at PhilRice could not have been conducted without the approval and support of Dr. Leo Sebastian and the help of Jimmy Quilang. The ASD group was very supportive during my stay and the field assistants Buddy, Silyo, and Jordick did their best to make the experiment a success. Special thanks to Joan, Mahsa and Dr. Segari for their friendship and hospitality.

For the China component of this thesis, I am indebted to Prof. Lu Guoan of Huazhong University in Wuhan, and Prof. Li Yuanhua and Dr. Cui Yuanlai of Wuhan University. Prof. Lu always accompanied me to Tuanlin station and did a very good job in managing the field experiment there despite the distance from Wuhan and the other research site near Kaifeng in Henan province. Prof. Lu, thanks for all your arrangements, hard work, and patience (one time you waited until 3 a.m. at Wuhan airport after a 6 hour delay of my flight). Also special thanks to the station managers Mr. Wang Jianzhang and Mr. Chen Chongde, the field assistants, and the students Li Shunjiang, Long Shenrong, and Chen Xiuhong who spent most of the summer months at Tuanlin or otherwise were analyzing samples at Huazhong university.

Back in Wageningen there was a nice working atmosphere in the Haarweg building. I had the advantage of sharing office with a number of nice people who were interested in the kind of work I was doing in Asia and vice versa with special thanks to Wim, Ilse, Tom, Shibu, and Yin Xinyou.

I am very thankful for all the support and interest of my family throughout the years, especially my parents. *Pa en ma jullie hebben zoveel betekend voor ons de afgelopen jaren en hebben ons op allerlei manieren gesteund. Hartelijk dank daarvoor.* I am also thankful to my parents-in-law in China for their kindness, hospitality, and understanding during the past years. In this way I also want to thank Date Jan for his steadfast support throughout the years.

Last but not least I want to thank my wife Lei Ying for all that she endured during the past five years. There were (too) long periods of separation that seemed endless. Finally we are together with an extra little person around and I hope for many years to go.

Paul Belder Wageningen, June 2005

Funding

The main source of funding of the PhD-thesis research was a grant from Wageningen University and Research centre (Wageningen UR) in the Netherlands. Furthermore, the International Rice Research Institute (IRRI) provided fellowships for carrying out research in the Philippines. The experiments at Tuanlin in Hubei province in China were partly funded by ACIAR (Australian Center for International Agricultural Research) project LWR1/2000/030. Part of the scenario study at IRRI was supported by a grant from the international collaborative research project 'Comprehensive Assessment of Water Management in Agriculture'. The contributions by the funding agencies are acknowledged.

Contents

Frequently used abbreviations

ANR	Apparent N recovery
ANUE	Agronomic N use efficiency
AWD	Alternate wet-and-dry
CS	Continuously submerged
DAS	Days after sowing
DAT	Days after transplanting
ET	Evapotranspiration
FI	Flush irrigation
HI	Harvest index
INUE	Internal N use efficiency
IRRI	International Rice Research Institute
MSD	Mid-season drainage
MU01	Muñoz 2001 growing season
PhilRice	Philippine Rice Research Institute
PI	Panicle initiation
RF	Rainfed
SNS	Submerged-nonsubmerged
SWP	Soil water potential
TL00	Tuanlin 2000 growing season
TL01	Tuanlin 2001 growing season
TL02	Tuanlin 2002 growing season
TL99	Tuanlin 1999 growing season

CHAPTER 1

General introduction

Rice is with wheat and maize among the three most important food crops in the world. In Asia, where 90% of rice is produced and consumed, rice is the predominant staple crop. In some south-Asian countries like Myanmar and Bangladesh, rice provides up to 75% of the daily calorie uptake (IRRI, 2002). A recent study estimated that the demand for rice will increase with 10–20% over the period 2005–2025 based on population growth and an expected diet change (Smil, 2005). The increase in rice production has to come from higher yield/area because land area under rice in Asia is declining (Papademetriou, 2000).

Rice is a crop that can be grown under a range of soil types, climates, and ecosystems. IRRI classifies rice ecosystems into four categories (Khush, 1997):

- Irrigated lowland areas with assurance of irrigation water;
- Rainfed lowlands with bunded fields, without irrigation water supply;
- Upland areas that are rainfed, well-draining, and without water ponding;
- Flood-prone areas where rice grows under rainfed dryland or shallow flooding conditions for 1–3 months before being flooded to depths of over 50 cm for a month or longer.

At present, irrigated lowland rice accounts for 75% of the rice production in Asia. Compared to the dependence on rainfed agriculture in the past, availability of irrigation made rice cropping less risky in many areas and made it possible to grow rice in seasons with insufficient rainfall and on more water-permeable soils. Because of more secure water supply under irrigated conditions, farmers do manage their crop more intensively leading to higher yields than in rainfed ecosystems (Khush, 1997). There are also intermediate systems among the four types: rainfed systems with water ponds that supply limited amounts of irrigation, whereas water supply within irrigation systems can be locally insufficient resulting in rainfed conditions during part of the season. The latter situation occurs more often due to increased competition for fresh water between agriculture and other sectors such as industries and cities. So rice production yet faces another major challenge: the yields per unit of land have to be maintained with a diminishing water supply in irrigation systems.

Water saving technologies on field scale

Rice farmers tend to keep their fields continuously submerged (CS) to be assured of ample water supply to the crop and to control weeds. To conserve water in the paddy, farmers construct bunds to prevent run-off and prepare their fields by repeated ploughing and harrowing of saturated soil, a process referred to as ‘puddling’, to create a layer with high resistance to percolation.

The decline in water availability in irrigation systems has led to water-saving technologies besides the common practices of bund construction and puddling. On the field scale these technologies include periods of nonsubmergence named ‘alternate-wet-and-dry’ or ‘intermittent irrigation’ (Dong et al., 2004; Tabbal et al., 2002), continuous soil saturation (Borrell et al., 1997), and direct dry-seeding. More recently, a system called ‘aerobic rice’ was developed, where rice is grown in nonpuddled and nonsaturated soil, just like an upland crop (Bouman et al., 2005; Yang et al., 2005). The difference with the traditional upland system is the use of supplementary irrigation, of higher yielding cultivars, and of other inputs such as nutrients and biocides. Aerobic rice systems therefore aim at medium to high yields. A revised overview of rice ecosystems by water management strategies is presented in Table 1 (Bouman, 2001). Rainfed lowland rice is marked as a system with alternate wetting and drying, but has in common with upland rice that there is no (supplemental) irrigation available. The qualifications ‘favourable’ and ‘unfavourable’ should be interpreted as areas where attainable yields are medium-high and low, respectively.

In literature, water-saving technologies show a range of responses in terms of amount of water saved and effect on yield. This variation can be ascribed to differences in weather, soil type, cultivar, and other management practices such as nutrients and will be investigated in this thesis.

Water use efficiency and water productivity

Water use efficiency in crop production can be defined in many ways such as:

- Amount of water (evapo)transpired per amount of irrigation water applied (IUE, $m^3\ m^{-3}$).
- Amount of yield (or biomass) per amount of water use (WP, kg m^{-3}).

The first definition can be interpreted as irrigation use efficiency (IUE), and the second definition reflects the water productivity. IUE can be computed for various scales such as a field or a whole basin (Barker et al., 1999). A low IUE can be regarded as inefficient use of irrigation water. Recently, Seckler (1996) argued that losses on field scale may be used for evapotranspiration downstream and IUE is best computed for the basin level. Effective water management then consists of reducing water flows to sinks such as saline aquifers, and seas, and upgrade water use from low to higher valued use. Other reports offer a wide range of management options to reduce irrigation water losses, such as Guerra et al. (1998), Tuong (1999), and Hamdy et al. (2003).

Table 1. Classification of rice production systems by water management strategies (after Bouman, 2001).

Flooded lowland → Dryland

Characteristic	Lowland (anaerobic)				Aerobic	
	Conventional flooded	Saturated soil culture	Alternate wetting and drying		Aerobic rice	Upland rice
			Irrigated	Rainfed		
Hydrology	Flooded	Saturation	Flooded ↔ aerobic	Flooded ↔ aerobic	Aerobic	Aerobic
Irrigation	Irrigated	Irrigated	Irrigated	Rainfed	Irrigated, rainfed	Rainfed
Tillage	Puddled, nonpuddled	Puddled, nonpuddled	Puddled, nonpuddled	Puddled, nonpuddled	Nonpuddled	Nonpuddled
	Bunded	Bunded	Bunded	Bunded	Bunded	Nonbunded
Environment	Favourable lowland	Favourable lowland	Favourable lowland	Unfavourable lowland	Favourable upland, Unfavourable lowland	Unfavourable upland
Germplasm	Lowland	Lowland	Lowland	Lowland	Improved upland × lowland	Upland
Yield level	High	High	High-medium	Medium-low	High-medium	Low

Water productivity (WP) expresses the output/input relation or 'crop per drop' (Kijne et al., 2003). WP can be computed as grain yield divided by total water input (WP_{I+R}) or by evapotranspiration (WP_{ET}). WP_{ET} values in rice found in literature showed a large range between 0.6 kg m^{-3} and 1.6 kg m^{-3} (Zwart and Bastiaanssen, 2004), caused by environmental factors (season, vapour pressure deficit), crop management (crop nutrition and protection), and genotypic variation (photosynthetic efficiency and stomatal conductance) (Turner, 1997).

Rice is a C_3 species and has a lower assimilation rate and higher stomatal conductance and thus a lower intrinsic water use efficiency than a C_4 species such as maize (Wong et al., 1979). This has provoked researchers to look into options to change rice into a C_4 species (Sheehy and Mitchell, 2001).

Water × nitrogen interaction

Nitrogen (N) is the most important nutrient in rice production and limits crop growth and yield in almost all environments if it is not added to the crop (Yoshida, 1981). N is in most cases added as inorganic fertilizer, although organic fertilizers are also used sometimes to enhance N availability. N is a constituent in all nucleic acids and proteins that allow plants to grow and survive. Since N is essential in these abundant molecules, most plant tissues invariably require minimum amounts of N to grow. One major consequence of a lack of N in plants is that the growth of leaf area will be reduced thereby limiting light interception, photosynthetic rate, and finally biomass growth and grain yield (Sinclair, 1990) and as a consequence WP_{I+R} and WP_{ET} will be lower. Resource use efficiency of fertilizer N in lowland rice is often low. Cassman et al. (2002) found an average apparent N recovery of 31% in farmers fields although higher values of 80% can be obtained under specific conditions (Schnier et al., 1990; Peng and Cassman, 1998; Liu et al., 2004). The variation in apparent N recovery is ascribed to dosing and timing, imbalanced nutrition, pests and diseases, and also to the water regime.

In CS fields, N is almost solely available as ammonium (NH_4) and N losses are predominantly through NH_3 volatilization (Vlek and Craswell, 1981). Allowing the soil to become (temporarily) aerobic will enhance nitrification. If the nitrate (NO_3) is not taken up, it is prone to denitrification losses (Reddy and Patrick, 1976; Eriksen et al., 1985) or leaching in more permeable soils (Keeney and Sahrawat, 1986). From a plant nutritional point of view, a mixture of NH_4 and NO_3 is better for N uptake and growth of the rice plant than the sole availability of NH_4 or NO_3 (Ta et al., 1981; Qian et al., 2004). Therefore, water-saving regimes may lead to higher N uptake and biomass growth, but may also lead to higher N losses and a reduced biomass growth if availability of NO_3 mismatches the crop N demand.

Crop modelling

The two main determinants for crop growth for a given cultivar are weather and management. Crop models are ideal tools to quantify both factors and moreover simulate the complex interactions that determine productivity of rice systems (Muchow and Kropff, 1997). Crop models are also ideal to extrapolate experimental data to other environments and sites if calibrated and evaluated for the target environments (Bouman et al., 1996). For model development and verification, data of field experiments are needed (Muchow and Kropff, 1997). Examples of rice growth models are CERES-Rice (Timsina and Humphreys, 2003) and ORYZA2000 (Bouman et al., 2001). ORYZA2000 simulates rice growth for potential, water-limited, and/or N limited conditions. The model was recently evaluated for N limited conditions by Bouman and Van Laar (2005) and for rainfed conditions by Boling et al. (2005), showing good agreement between simulated and observed LAI, biomass, and grain yield and for water-limited conditions also for soil water potential and field water depth. A further step is the evaluation of the model for water-saving strategies in irrigated lowland rice. Next the ORYZA2000 model can be used to explore options for water saving under a wide range of soil and weather conditions.

Target environments

Field experiments were conducted at three different sites, (1) Tuanlin in China, (2) Muñoz in the Philippines and (3) Los Baños in the Philippines. The sites at Tuanlin and Muñoz are located within Zhanghe Irrigation System (ZIS) and the Upper Pampanga River Integrated Irrigation System (UPRIIS), respectively. The site at Los Baños belongs to the experimental farm of the International Rice Research Institute (IRRI) with local irrigation supplies.

China

ZIS is located in Hubei province north of the Changjiang (Yangtze River) in central China and has a command area of approximately 160,000 ha. Most of the irrigation water is supplied by the Zhanghe Reservoir, built between 1958 and 1966 on a tributary of the Changjiang. Within the system are countless medium to small reservoirs, small basins, and pump stations that are partly incorporated and partly operating independently from the system. The reservoir was designed not only for irrigation but also for power generation, domestic and industrial uses, navigation, and flood control (Loeve et al., 2004). Rice cultivation accounts for about 80% of the total irrigated area and rice is together with winter wheat the main grain crop in the area.

In Figure 1, the annual water allocation for irrigation and other uses over the period 1965–1998 in ZIS is shown. Over the past decades, water demand from municipalities, industries, and power generation has increased resulting in a drop of irrigated rice area from 130,000 ha in the seventies of the last century to 76,000 ha in the nineties of the last century. At the same time average yield increased from 4.0 to 8.0 t ha^{-1} resulting in total rice production that still increased with around 16%. The reduction of irrigation water delivered to rice production decreased by around 2/3, thus leading to an enormous improvement of WP_{I+R} of the ZIS area. The improved WP_{I+R} can be ascribed to (Hong et al., 2001):

- Economic and institutional reforms initiated in 1978;
- Volumetric pricing of water;
- Adoption of water-saving practices such as alternate wet-and-dry;
- A shift form growing one crop instead of two crops per summer season;
- Increased recapture and reuse of return flows through the network of reservoirs.

Some farmers are not practising water-saving technologies because they are unsure about availability of water (Moya et al., 2004).

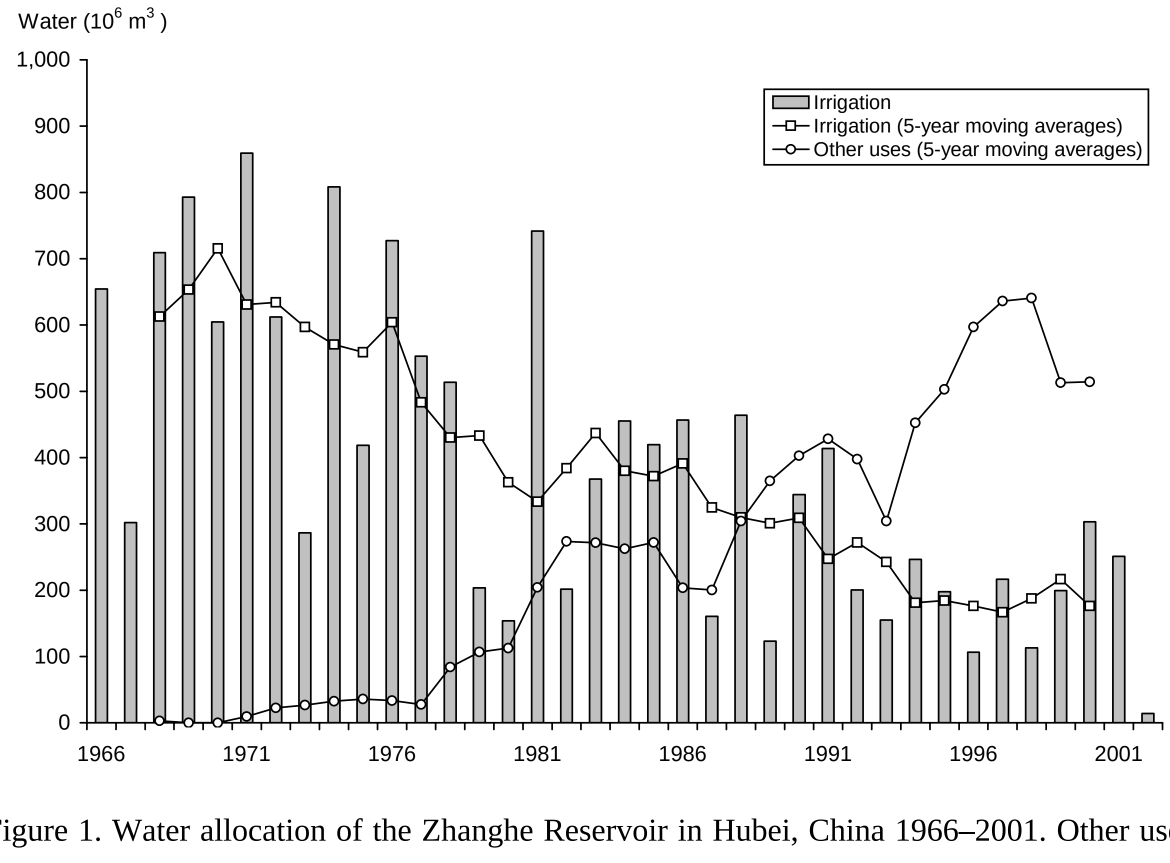

Figure 1. Water allocation of the Zhanghe Reservoir in Hubei, China 1966–2001. Other uses represent municipal, industry, hydropower and flood releases. Data source: Loeve et al. (2004).

Philippines

UPRIIS is located in central-Luzon, which is considered as the rice bowl of the Philippines. Irrigation plays an important role in central-Luzon, since rice farming is the major source of employment and income (Hafeez, 2003). Availability of irrigation declined due to increased competition with industries and cities. This is clearly depicted in the case of the Angat Reservoir in Bulacan province (Pingali et al., 1997). Other reasons for a reduced amount of irrigation water for rice in central-Luzon are pollution of the Agno river in Pangasinan province by mining activities upstream (Castañeda and Bhuiyan, 1993) and destruction of irrigation structures by earthquakes in 1990 and the eruption of the Pinatubo in 1991 (Hafeez, 2003).

UPRIIS is divided into four districts and Muñoz is located in district 1. Around 60% of the area in district 1 was used for rice cropping in the dry season of 2001. Especially at the tail end of district 1, irrigation water in the dry season of 2001 was short and farmers were growing upland crops such as water melon, tomato, onion, egg plant, chili, and white squash (Hafeez, 2003). Field observations by Hafeez (2003) reported poor maintenance of irrigation structures, often resulting in siltation and clogging of canals. Tail-end portions had serious water deficiencies, whereas the upper portions had excess water.

Research objectives

The main goal of this thesis was to quantify the effects of water-saving regimes on water productivity, N-use efficiency, and yield by a combined experimental and modelling approach. Various water regimes were studied at three sites in consecutive growing seasons. Furthermore, the study aimed at gaining more insight in the role of subsurface hydrology on water (saving) regimes. The study also determined water balances of CS and water-saving regimes, to quantify the components evaporation, transpiration and percolation in each water regime. The water balance components evaporation, transpiration, and percolation were calculated for different water regimes. A modelling approach was used to gain insight in how water-saving regimes would affect water use and yield under future scenarios of deeper groundwater table depths and how weather and soil permeability would affect these relationships.

The final goal of the study was to explore options for water saving at the field scale in the target environments and their consequences for yield security and water use at regional scale.

Thesis outline

The thesis consists of an introduction (Chapter 1), four research papers (Chapters 2–5), and a general discussion (Chapter 6).

Chapter 2 presents a hydrological characterization of the field experiments and analyses the effects of various water-saving regimes on yield, WP_{I+R}, and N economy.

Chapter 3 deals with the role of N on yield formation and water productivity. Different water regimes are compared in terms of water use, WP_{ET}, and N use efficiencies (apparent N recovery, internal N use efficiency). The concept of a critical N concentration in crops was used to analyse effects of water regime, N dose, and cultivar on crop growth and yield.

In Chapter 4, effects of continuously submerged and aerobic rice on water and N use, crop growth, and yield are presented. Two methods to determine the apparent N recovery were compared and discussed and the ^{15}N isotope study was used to determine the N balance.

In Chapter 5, effects of water saving on water balance components and yield were quantified with the rice growth model ORYZA2000. First, the performance of ORYZA2000 was evaluated by statistical comparison between observed and simulated values of crop and soil water variables. Second, water balances for water regimes reported in Chapters 2–4 were computed. Finally, water balance components and yield were calculated with historic weather data.

In the general discussion in Chapter 6 the prospects and limitations for a comprehensive assessment of the impact of water saving on yield, water productivity and the reduction of water losses is discussed. Furthermore, the main conclusions are presented.

CHAPTER 2

Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia[1]

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Abstract
With decreasing water availability for agriculture and increasing demand for rice, water use in rice production systems has to be reduced and water productivity increased. Alternately submerged-nonsubmerged (SNS) systems can save water compared with continuous submergence (CS). However, the reported effect on yield varies widely and detailed characterizations of the hydrological conditions of SNS experiments are often lacking so that generalizations are difficult to make. We compared the effects of SNS and CS on crop performance and water use, at different levels of N input, in field experiments in China and the Philippines, while recording in detail the hydrological dynamics during the experiments. The experiments were conducted in irrigated lowlands and followed SNS practices as recommended to farmers in China. The sites had silty clay loam soils, shallow groundwater tables and percolation rates of 1.0–4.5 mm d^{-1}.
Yields were 4.1–5.0 t ha^{-1} with 0 kg N ha^{-1} and 6.8–9.2 t ha^{-1} with 180 kg N ha^{-1}. Biomass and yield did not significantly differ between SNS and CS, but water productivity was significantly higher under SNS than under CS in two out of three experiments. There was no significant water x N interaction on yield, biomass, and water productivity. Combined rainfall plus irrigation water inputs were 600–960 mm under CS, and 6–14% lower under SNS. Irrigation water input was 15–18% lower under SNS than under CS, but only significantly so in one experiment. Under SNS, the soils had no ponded water for 40–60% of the total time of crop growth. During the nonsubmerged periods, ponded water depths or shallow groundwater tables never went deeper than –35 cm and remained most of the time within the rooted depth of the soil. Soil water potentials did not drop below –10 kPa. We argue that our results are typical for poorly-drained irrigated lowlands in Asia, and that SNS can reduce water use up to 15% without affecting yield when the shallow groundwater stays within about 0–30 cm. A hydrological characterization and mapping of Asia's rice area is needed to assess the extent and magnitude of potential water savings.

Keywords: Lowland rice, water saving, nonsubmergence, nitrogen.

[1] Published in: Agricultural Water Management (2004) 65, 193–210.

Introduction

Rice is the most important staple in Asia, providing on average 32% of total calorie uptake (Maclean et al., 2002). Mainly because of a still-growing population, demand for rice is expected to keep increasing in the coming decades (Pingali et al., 1997). About 75% of the global rice volume is produced in the irrigated lowlands (Maclean et al., 2002). Decreasing water availability for agriculture threatens the productivity of the irrigated rice ecosystem and ways must be sought to save water and increase the water productivity of rice (Guerra et al., 1998).

Conventional water management in lowland rice aims at keeping the fields continuously submerged (CS). Water inputs can be reduced and water productivity increased by introducing periods of nonsubmerged conditions of several days throughout the growing season unless cracks are formed through the plough sole (Bouman and Tuong, 2001). In subtropical areas of China, systems of alternate submergence-nonsubmergence (SNS; also known as alternate wetting-and-drying, AWD) have been reported to maintain or even increase yield and to be widely adopted by farmers (Wu, 1999; Li, 2001; Mao Zhi, 1993). However, experimental evidence is still scarcely reported in international literature and the hydrological and environmental conditions under which these systems are practiced are not well known. When SNS systems were tested in tropical areas in Asia, such as in India and the Philippines, yields often decreased compared with CS conditions (Mishra et al., 1990; Tripathi et al., 1986; Tabbal et al., 2002). The different results between China and tropical Asia could have been caused by differences in specifications of the SNS systems tested (frequency and duration of the periods without submerged conditions), soil-hydrological conditions, groundwater table depth, rice variety used, and crop management such as nitrogen (N) fertilization (Bouman and Tuong, 2001; Tabbal et al., 2002). The actual frequency, duration and level of water stress during the nonsubmerged periods is probably the most important factor affecting yield, but, unfortunately, these are hardly ever recorded or presented in literature. This hampers the evaluation and comparison of SNS practices reported in literature.

In this paper, we evaluate the effectiveness of SNS through three years of field experiments in a temperate area in China and a tropical area in the Philippines. We quantify and compare yield and water use under SNS and CS regimes in typical lowland rice environments. The specifications of the SNS regimes are derived from the recommendations given to farmers at the site in China. To compare the two sites, we selected locations with comparable soil types and general hydrological conditions. Special attention is given to a detailed characterization of the soil-hydrological dynamics during the experiments. The experiments included low and high fertilizer-N inputs to study the effect of N availability on the performance of SNS. We discuss the results in terms of yield, water use, water productivity and N uptake, and relate these to the soil-hydrological conditions of the experiments. Finally we compare the results of our experiments with recently conducted experiments by others, and put these in the context of typical lowland rice producing areas in Asia.

Materials and methods

Location

Three field experiments were conducted in irrigated lowland rice areas. Two experiments were located in Tuanlin (30°52′ N, 112°11′ E), Hubei Province, China, at an altitude of 100 m, and were conducted in the summer seasons of 1999 (TL99) and 2000 (TL00). The experimental site was a farmer's field surrounded by lowland rice fields in the 160,000 ha Zanghe Irrigation System, see Loeve et al. (2004) for more details of the area. The third experiment was carried out at the experimental farm of the Philippine Rice Research Institute (PhilRice) in Muñoz (15º40′N, 120º54′E), Nueva Ecija Province, Philippines, at an altitude of 35 m, in the dry season of 2001. Our experimental field was surrounded by flooded rice fields, and the experimental farm itself is surrounded by lowland rice fields in the 100,000 ha Upper Pampanga River Integrated Irrigation System (see Tabbal et al., 2002, for more details of the area). Table 1 presents the main soil characteristics of the sites. In both Tuanlin and Muñoz, the soil texture was silty clay loam.

Treatments and design

Two common water regimes were tested in all experiments: (1) continuously submerged (CS) and (2) alternately submerged-nonsubmerged during the whole cropping season (SNS). At Muñoz, a third water regime was added, alternately submerged-nonsubmerged in the vegetative phase (SNSv), followed by continuous

Table 1. Soil characteristics in Tuanlin (0–20 cm) and Muñoz (0–15 cm).

Characteristic	Tuanlin	Muñoz
Texture		
% sand	13	8
% silt	48	45
% loam	39	47
pH (H_2O) 1:1	6.5	5.4
Organic C (%)	1.03	1.77
CEC (cmol kg^{-1})	20.6	17.1

submergence after panicle initiation (PI). The end of the vegetative phase was when the panicle primordia started to develop. Ponded water depth on the field in both the CS and SNS regimes was kept between 10 and 40 mm during the first 10 days after transplanting. After this 10-day period, the water level was allowed to fluctuate between about 10 and 100 mm in the CS regime. In the SNS regimes, 3- to 5-day periods without ponded water were introduced before each new irrigation application. The maximum water depth in the SNS regimes was 100 mm (any excessive rainfall was drained off). During the nonsubmerged periods, the ponded water level dropped below the field level. In the SNS treatments, a special period of about 10 days of nonsubmergence was imposed just before PI. During this period, no irrigation was given and any rainwater was drained off. This period is called ‘mid-season drainage’ or ‘sun baking’ in China and has been reported to increase yield (Mao Zhi, 1993).

Levels of N fertilizer were 180 kg ha^{-1} at TL99, 0 and 180 kg ha^{-1} at TL00, and 0, 90, and 180 kg ha^{-1} at Muñoz. At Tuanlin, 180 kg N ha^{-1} was applied as urea in different splits per subplot: (a) two splits: 50% basal and 50% 10 days after transplanting (DAT), (b) four splits: 30% basal, 30% 10 DAT, 30% at PI, and 10% at heading, and (c) six (1999) or four (2000) splits as follows: in 1999, the six splits of (c) were 25% basal, 25% 10 DAT, 20% at PI, 10% just before heading, 10% after heading, and 10% after complete flowering; in 2000, the four splits of (c) were 17% basal, 20% 16 DAT, 27% at mid-tillering, and 36% at PI. At Muñoz, the 90 and 180 kg urea-N ha^{-1} was applied as follows: 22% basal, 28% 25 DAT, 33% at PI, and 17% at flowering.

P and K were applied as basal to all treatments. P was applied at 25 kg ha^{-1} at Tuanlin and 30 kg ha^{-1} at Muñoz and K was applied at 70 kg ha^{-1} at Tuanlin and 100 kg ha^{-1} at Muñoz. All basal fertilizers were incorporated in the soil at the last harrowing one day before transplanting.

The design of the treatments was a split plot in complete randomized blocks with water regime as the main plot and N level as the subplot. Treatment combinations had three (TL99) or four replications (TL00 and Muñoz). Plot sizes varied from 88 to 201 m^2 at Tuanlin and were 84 m^2 at Muñoz. The crop was transplanted at 20 × 20-cm spacing with 3–5 seedlings per hill. Seedling age at transplanting was 32 and 38 days at TL99 and TL00 and 21 days at Muñoz.

Table 2 presents the cropping calendar of the three experiments. The varieties used at Tuanlin were the hybrids 2You501 in 1999 and 2You725 in 2000. At Muñoz, the inbred variety IR72 was used. Plots were regularly hand-weeded and pesticides were used to prevent insect and pest damage. No noticeable crop damage was observed in the experiments.

Table 2. Cropping calendar for the experiments at Tuanlin 1999 and 2000, and Muñoz 2001.

Experiment	Sowing	Transplanting	Panicle initiation	Flowering	Harvest
Tuanlin 1999	18 Apr	20 May	6 Jul	8–12 Aug	6–11 Sep
Tuanlin 2000	10 Apr	18 May	14–18 Jul	5–9 Aug	4–8 Sep
Muñoz 2001	28 Dec[a]	18–19 Jan	26 Feb	22 Mar	18–23 Apr

[a] in year 2000.

Crop measurements

Crop samples for biomass and N uptake at TL99 and TL00 were taken five times from transplanting onward. At TL99, the sampling days were 16, 33, 58, 95, and 109–114 DAT. At TL00, the sampling days were 17, 29, 57, 82, and 109–113 DAT. At Muñoz, the crop was sampled seven times at 0, 14, 28, 41, 62, 76, and 90–95 DAT. At each sampling, 12 hills per plot were pulled out (representing 0.48 m^2), washed, and processed. At Muñoz, 100 seedlings were sampled at transplanting. Dry weight of the plants was determined after drying at 70 °C when constant weight was reached.

Leaf area was determined at TL00 and Muñoz only. Grain yield was measured from a central 4.8- and 6-m^2 area at Tuanlin and Muñoz, respectively, and is reported at 14% moisture. The following yield components were determined from the 12-hill sample at maturity: grain density, percentage grain filling, and 1,000 (filled)-grain weight after drying at 70 °C for three days.

At Tuanlin, the N concentration of plant material was determined using the micro-Kjeldahl method following digestion and titration procedures as described by Bremner and Mulvaney (1982). At Muñoz, the Dumas-method as described by Bergersen (1980) was used.

Water measurements

At both sites, the amounts of irrigation and drainage were measured throughout the growing season. Irrigation water was determined using flow meters installed in the irrigation pipes at Tuanlin and using cut-throat flumes and V-notch weirs at Muñoz.

At Tuanlin, ponded water depths were measured in each subplot with perforated tubes of 30 cm height that could record both above-ground and below-ground water level. During periods of nonsubmergence, the ponded water level dropped below the surface level and was recorded as ‘negative ponded water’ depth. At Muñoz, the ponded water depth was measured with sloping gauges that could not record negative (below surface level) values. To record the shallow subsurface water dynamics, six plastic tubes of 1.75 m depth that were perforated 50 cm from the top downwards, were installed in the bunds between each replicate. The water level recorded in these tubes is referred to as 'groundwater depth'. To prevent seepage between plots with different water regimes, plastic sheets were installed in the bunds down to a depth of 40 cm at both locations. This was well below the top of the hardpan, which was about 20 cm deep at both locations. At Muñoz, tensiometers were installed to determine soil water potential at 10-cm depth in SNSv and SNS treatments (no tensiometers were available at Tuanlin). The percolation rate was measured inside covered metal cylinders at both sites in CS plots by daily recording of the ponded water levels. Daily weather data were collected from weather stations at the sites, and included rainfall, radiation, and temperature.

Calculations and statistical analysis

Statistical analyses consisted of analysis of variance (ANOVA), with water and N regime as main and subfactor, respectively. When water or N effects were significant, pair-wise-testing with the *t*-test was done among water or N regimes. A separate *t*-test was performed to analyze the effect of water regime on water productivity at 180 kg N ha^{-1}, although the water factor was not significant in ANOVA. The level of confidence was set at 95%. Harvest index was calculated as the weight of the harvestable product (i.e., grains for rice) divided by the total above-ground biomass of the rice plant. Water productivity (kg grain m^{-3} water) was calculated as grain yield divided by total water input (drainage water subtracted) from rainfall and irrigation (WP_{I+R}).

Results

Weather

Monthly-average values of minimum and maximum temperature, radiation, and cumulative monthly rainfall are presented in Table 3. Rainfall in the summer seasons at Tuanlin was much higher than rainfall in the dry season at Muñoz. At Tuanlin, cumulative rainfall from transplanting till maturity was 377 mm in 1999 and 463 mm in 2000, which was lower than the 1990–1998 average of 566 mm for the same period. At Muñoz, cumulative rainfall from transplanting till maturity in 2001 was 91 mm, which was almost twice as high as the 1990–2000 average of 51 mm. Daily average temperatures from transplanting until harvest were quite comparable between the experiments with 26.1, 26.7, and 27.2 °C for TL99, TL00, and Muñoz, respectively. Cumulative radiation from transplanting till harvest was 2,168, 2,243, and 1,919 MJ m^{-2} for TL99, TL00, and Muñoz, respectively. Cumulative radiation at Muñoz was about 10–15% less than at Tuanlin, due to a shorter growing season.

Table 3. Monthly rainfall (mm), mean maximum temperature (°C), mean minimum temperature (°C), and mean daily radiation (MJ m^{-2} d^{-1}) at Tuanlin 1999 and 2000 and Muñoz 2001.

Month	Rainfall	T max	T min	Radiation
Tuanlin 1999				
May	162	27.4	15.3	18.5
June	153	27.9	21.6	17.4
July	94	30.5	23.7	19.2
August	52	30.8	23.4	19.9
September	50	29.5	20.9	17.1
Tuanlin 2000				
May	101[a]	28.4	18.2	21.0
June	49	30.1	20.2	20.7
July	112	32.3	26.3	20.6
August	186[b]	31.1	23.7	20.0
September	-	26.7[c]	18.8[c]	16.3[c]
Muñoz 2001				
January	19	30.3	22.8	19.7
February	24	30.2	22.5	17.3
March	30	31.3	22.7	21.0
April	29	34.2	24.1	22.4

[a] measured from 20 May onward;

[b] measured until 26 August;

[c] measured until 10 September.

Water regime and water use

Daily rainfall and ponded water depths in the field for CS and SNS are presented in Figure 1. In CS, water depths fluctuated roughly from 5 to 90 mm at both sites. In SNS, the depths fluctuated from about –200 to 90 mm at Tuanlin. At Muñoz, maximum ponded water depths were about 60 mm. The shallow groundwater depths fluctuated between –350 to –60 mm until one week before harvest, indicating that ponded water depths also never went deeper than –350 mm. The percentage of days without standing water in SNS was 39% at TL99, 45% at TL00, and 59% at Muñoz. The frequency of nonsubmerged periods in SNS at Tuanlin was less in 2000 than in 1999 because of more rainfall in the grain-filling phase in 2000. The relatively long dry period just before panicle initiation in SNS is the mid-season drainage.

Figure 2 presents the soil water potential at 10 cm and the shallow groundwater

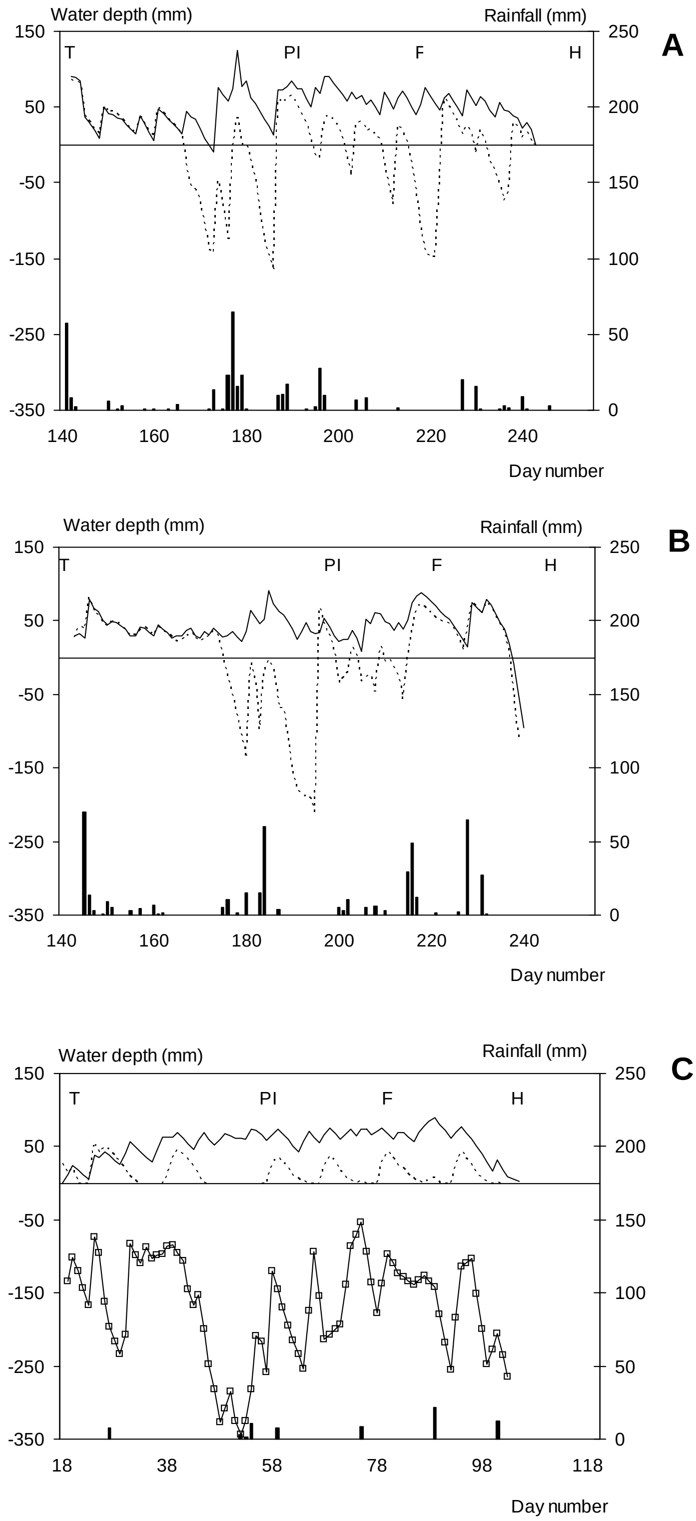


Figure 1. Ponded water depth in CS (—) and SNS (----) and daily rainfall (vertical bars) at (A) Tuanlin 1999, (B) Tuanlin 2000, and (C) Muñoz 2001. For Muñoz the shallow groundwater depth is represented by a full line with □. The average standard error for water depth was 5.1 mm in CS and 13.2 mm in SNS in TL99, 4.6 mm in CS and 9.4 mm in SNS in TL00, and 7.6 mm in CS and 5.0 mm in SNS at Muñoz. The abbreviations indicate crop stages: T = transplanting, PI = panicle initiation, F = flowering, and H = harvest.

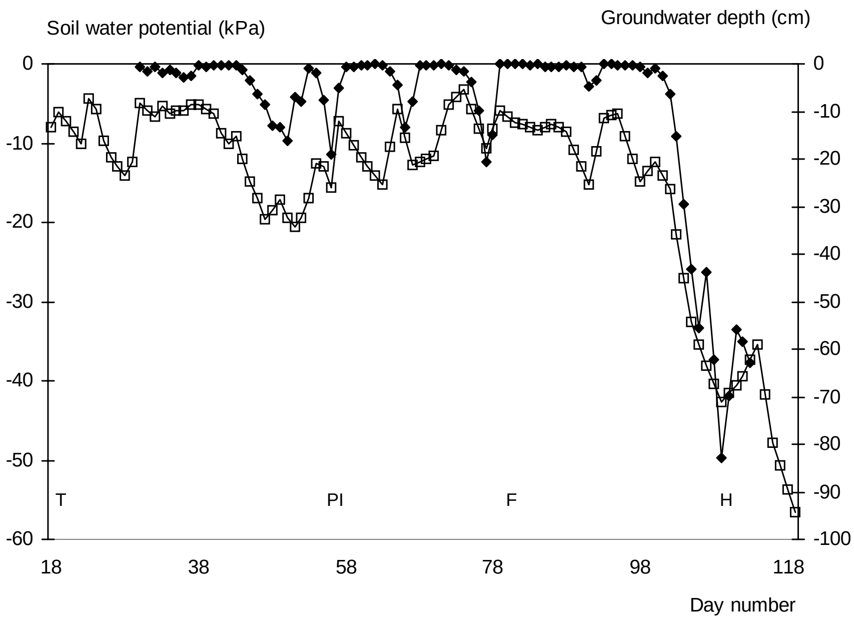


Figure 2. Soil water potential at 10 cm depth in SNS regime (♦) and groundwater table depth (□) at Muñoz 2001. The average standard error was 3.3 kPa in soil water potential and 5.0 cm in groundwater table depth. The abbreviations indicate crop stages: T = transplanting, PI = panicle initiation, F = flowering, and H = harvest.

table depth at Muñoz. The groundwater depth was not deeper than 35 cm from transplanting to about a week before harvest, and was most of the time well within the root zone. As a consequence, water potentials were never very low (< –10 kPa) until a fortnight before final harvest. Although water potentials were not measured at Tuanlin, we can assume that they also never dropped below –10 kPa since the ponded water depths never dropped below 200 mm below the surface. At the end of the season at Muñoz, when our and all the surrounding fields were drained, the groundwater depth dropped rapidly. At the same time the soil water potential dropped to –40 kPa.

Mean percolation rates in CS plots were 4.5 mm d^{-1} at Tuanlin and 1 mm d^{-1} at Muñoz. Total (irrigation plus rain) water inputs minus drainage ranged from 518 to 965 mm $season^{-1}$ (Table 4). Irrigation water input in SNS was 15–18% lower than in CS, but this difference was statistically significant only at Muñoz.

Crop growth and development

N levels highly affected leaf area development and crop growth. However, at each N level, differences between CS and SNS were relatively small (Figures 3 and 4). The maximum leaf area index (LAI) at TL00 was 3.3 in 0-N plots and 9.9 in CS-plots that received 180 kg N ha^{-1}. At Muñoz, the maximum LAI was 1.5 in 0-N plots and 5.3 in 180-N plots. At TL00, the LAI at PI and flowering was significantly higher in CS

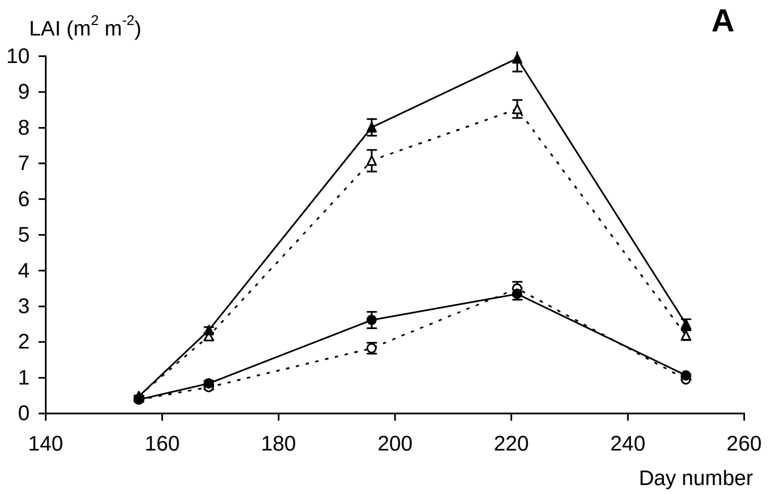
Table 4. Irrigation water inputs (mm) in the three experiments. Rainfall was 377, 463 and 91 mm season^{-1} for Tuanlin 1999, Tualin 2000, and Muñoz, respectively.

Experiment	CS[a]	SNS[b]	SNSv[c]
Tuanlin 1999	588 ± 93	501 ± 142	-
Tuanlin 2000	415 ± 37	339 ± 54	-
Muñoz 2001	511 ± 23	427 ± 15	489 ± 31

[a] CS = continuously submerged.

[b] SNS = alternately submerged-nonsubmerged during the whole cropping season.

[c] SNSv = alternately submerged-nonsubmerged in the vegetative phase only.



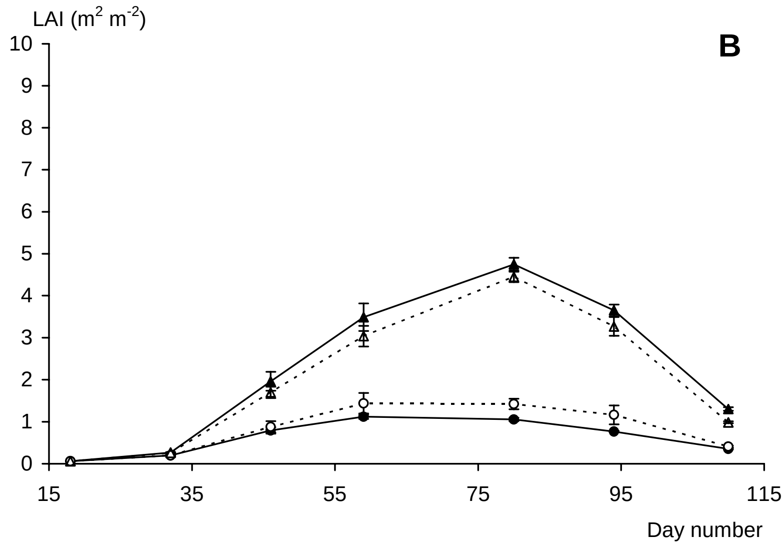


Figure 3. Leaf area index (LAI) in time in CS (—) and SNS (----) at N levels of 0 (○, •) and 180 kg ha^{-1} (Δ, ▲) at (A) Tuanlin 2000 and (B) Muñoz 2001; bars represent the standard error.

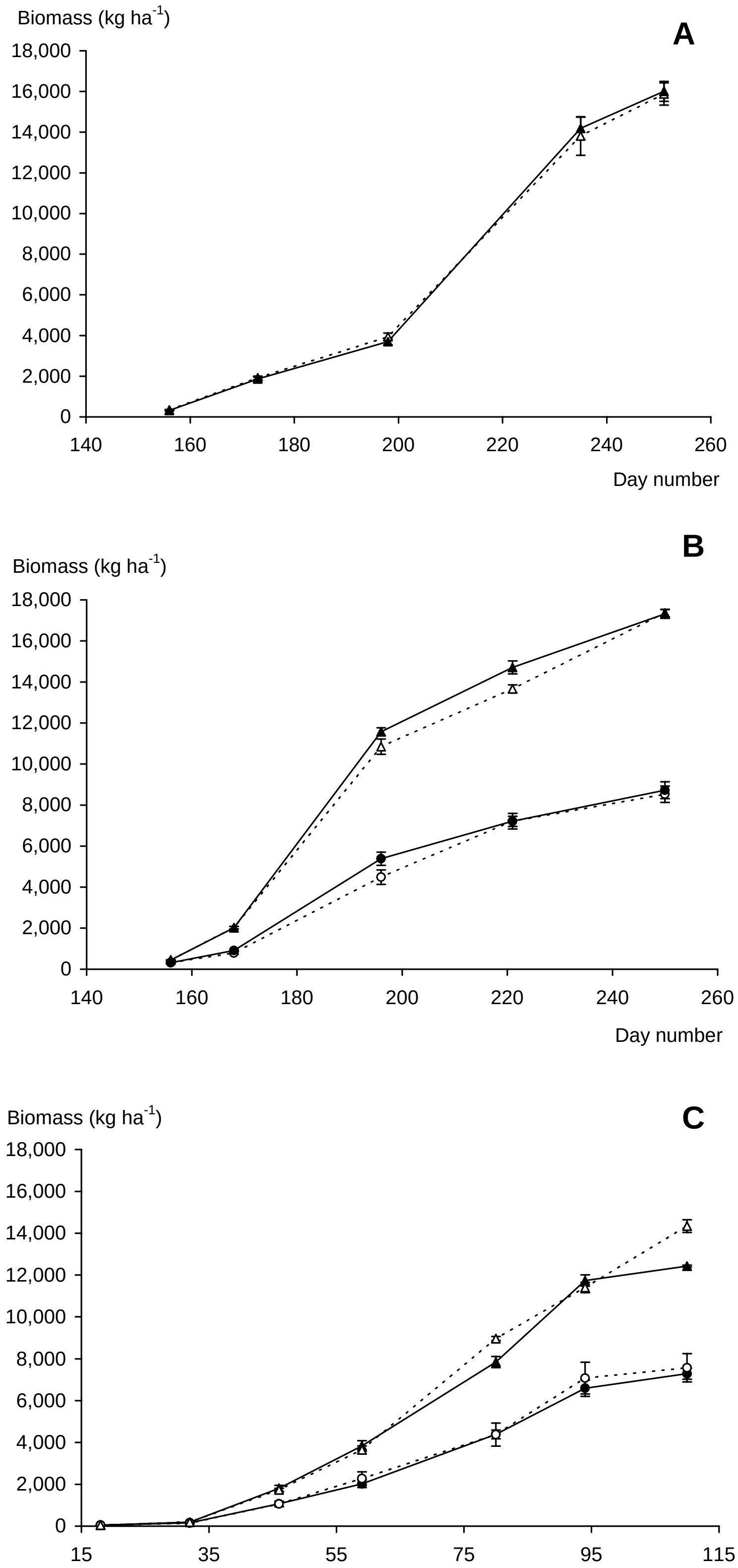


Figure 4. Total above-ground biomass in time in CS (—) and SNS (---) at N levels of 0 (○, •) and 180 kg ha^{-1} (Δ, ▲), at (A) Tuanlin 1999, (B) Tuanlin 2000 and (C) at Muñoz 2001; bars represent the standard error. At Tuanlin, the data for 180 kg N ha^{-1} are the average of the three subtreatments on fertilizer splits.

than in SNS. At Muñoz, the LAI at these growth stages was also higher in CS than in SNS, but the differences were not significant.

Water regime did not affect crop development rate in any of the experiments. With 0-N, the crop matured 5 days earlier than the crop that received 180 kg N ha^{-1}.

Grain yields ranged from 4.1 to 5.0 t ha^{-1} in 0-N plots and from 6.8 to 9.2 t ha^{-1} in 180-N plots (Table 5). Higher grain yields were obtained at Tuanlin with the hybrids than at Muñoz with the inbred variety. These higher yields are partly explained by a 33-day longer growth period of the hybrids. At 180 kg N ha^{-1}, grain yield was 4% and 7% higher in SNS than in CS at TL00 and Muñoz, respectively, while it was 4% lower in SNS than in CS at TL99. However, none of these differences was statistically significant. Increasing the number of splits of N fertilizer in SNS increased grain yield at Tuanlin in 1999 but not in 2000 (a detailed analysis of the effect of N-splits at Tuanlin is presented by Cabangon et al., 2001). SNSv at Muñoz did not result in a significantly higher yield than SNS.

Total above-ground biomass data at harvest are presented in Table 6. There were no significant differences in biomass between water regimes and there were no significant interaction effects between water regime and N level. The highest biomass (18 t ha^{-1}) was observed with the hybrid variety 2You725 at Tuanlin in 2000.

The harvest index was significantly affected by water regime but not by N level at Muñoz: HI was 0.51–0.53 in CS and 0.47–0.48 in SNS. This trend was not found at TL00, where HI was 0.43 in CS and 0.45 in SNS, calculated as the average over all N regimes. HI at TL99 was on average 0.52 and was hardly affected by N level or water regime.

Water productivity

Water productivity (WP_{I+R}) ranged from 0.50 to 1.13 kg m^{-3} at Tuanlin and from 0.73 to 1.48 kg m^{-3} at Muñoz (Table 7). The relatively high values at even low yield levels compared to reported WP_{I+R} by Bouman and Tuong (2001) may have been caused by a larger proportion of water taken up from the shallow groundwater in our experiments. Water productivity increased significantly with N fertilizer rate. At 180 kg N ha^{-1}, water productivity was significantly higher in SNS than in CS, for both TL00 and Muñoz. At 0 and 90 kg N ha^{-1}, water productivity was not significantly higher in SNS than in CS.

Yield components

Grain formation was significantly affected by N level at TL00 and Muñoz. The number of grains per square meter, or grain density, ranged from 22 to 27 × 10^3 m^{-2} in 0-N plots, and from 34 to 45 × 10^3 m^{-2} in 180-N plots (Table 8). At Muñoz, grain

Table 5. Grain yield (t ha^{-1}) for the three experiments.

	Tuanlin 1999		Tuanlin 2000	
N regime (kg ha^{-1})	CS[a]	SNS[b]	CS	SNS
0	-	-	4.4 a	4.5 a
180 (2 splits)	9.2	6.8	8.2 b	8.9 b
180 (4 splits, early)	8.4	8.0	8.1 b	8.4 b
180 (4 splits ’99, 6 splits ’00)	8.1	8.4	8.7 b	8.7 b

	Muñoz 2001		
N regime (kg ha^{-1})	CS	SNSv[c]	SNS
0	4.4 a	5.0 a	4.1 a
90	6.7 b	6.7 b	6.4 b
180	7.2 b	7.7 b	7.6 c

Statistical differences (P≤0.05) between N rates are indicated by different lower-case letter.

[a] CS = continuously submerged.

[b] SNS = alternately submerged-nonsubmerged during the whole cropping season.

[c] SNSv = alternately submerged-nonsubmerged in the vegetative phase only.

Table 6. Total above-ground biomass at harvest (t ha^{-1}) for the three experiments.

	Tuanlin 1999		Tuanlin 2000	
N regime (kg ha^{-1})	CS[a]	SNS[b]	CS	SNS
0	-	-	8.7 a	8.5 a
180 (2 splits)	16.9	14.7	17.1 b	17.9 b
180 (4 splits, early)	16.2	16.0	16.7 b	16.8 b
180 (4 splits ’99, 6 splits ’00)	16.1	17.2	18.1 b	17.4 b

	Muñoz 2001		
N regime (kg ha^{-1})	CS	SNSv[c]	SNS
0	7.3 a	8.6 a	7.6 a
90	11.3 b	11.6 b	11.7 b
180	12.4 b	13.7 c	14.3 c

Statistical differences (P≤0.05) between N regimes are indicated by different lower-case letter.

[a] CS = continuously submerged.

[b] SNS = alternately submerged-nonsubmerged during the whole cropping season.

[c] SNSv = alternately submerged-nonsubmerged in the vegetative phase only.

Table 7. Water productivity (kg grain m^{-3}) for the three experiments.

N regime	Tuanlin 1999 CS[a]	Tuanlin 1999 SNS[b]	Tuanlin 2000 CS	Tuanlin 2000 SNS
0	-	-	0.50 a	0.58 a
180 (2 splits)	0.98	0.83	0.94 b	1.13 b
180 (4 splits, early)	0.90	0.95	0.92 b	1.07 b
180 (4 splits '99, 6 splits '00)	0.86	1.03	0.99 b	1.07 b

N regime (kg ha^{-1})	Muñoz 2001 CS	Muñoz 2001 SNSv[c]	Muñoz 2001 SNS
0	0.73 a	0.87 a	0.78 a
90	1.11 b	1.16 b	1.24 b
180	1.20 b	1.34 b	1.48 c

Statistical differences (P≤0.05) between N regimes are indicated by different lower-case letter.

[a] CS = continuously submerged.

[b] SNS = alternately submerged-nonsubmerged during the whole cropping season.

[c] SNSv = alternately submerged-nonsubmerged in the vegetative phase only.

Table 8. Grains m^{-2} (×1,000) for the three experiments.

N regime (kg ha^{-1})	Tuanlin 1999 CS[a]	Tuanlin 1999 SNS[b]	Tuanlin 2000 CS	Tuanlin 2000 SNS
0	-	-	24.0 a	22.0 a
180 (2 splits)	45.0	35.8	41.9 b	42.1 b
180 (4 splits, early)	42.8	44.1	41.5 b	37.1 b
180 (4 splits '99, 6 splits '00)	41.9	43.5	39.8 b	40.1 b

N regime (kg ha^{-1})	Muñoz 2001 CS	Muñoz 2001 SNSv[c]	Muñoz 2001 SNS
0	21.7 Aa	27.1 Ba	25.0 ABa
90	33.8 Ab	37.3 Ab	34.6 Ab
180	41.1 Ac	42.1 Ac	39.2 Ac

Statistical differences (P≤0.05) between columns are indicated by different upper-case letter and statistical differences (P≤0.05) between rows are indicated by different lower-case letter.

[a] CS = continuously submerged.

[b] SNS = alternately submerged-nonsubmerged during the whole cropping season.

[c] SNSv = alternately submerged-nonsubmerged in the vegetative phase only.

density was also significantly affected by water regime at the 0-N level, at which SNSv had a significantly higher grain density than CS. The average (filled) 1,000-grain weight was 23.7 ± 0.2, 25.6 ± 0.2, and 21.2 ± 0.5 g for TL99, TL00, and Muñoz, respectively. Differences reflect genotypic differences. The coefficient of variance was less than 5%, indicating the stability of this variable. The percentage filled grains was also not significantly affected by water regime. This percentage was 87–94% in the hybrid varieties at Tuanlin. At Muñoz the percentage filled grains in the inbred IR72 was significantly affected by N regime and was 85%, 81% and 77% at 0, 90, and 180 kg N ha^{-1}, respectively.

Nitrogen uptake and recovery

N uptake of the inbred rice at Muñoz was 46–59 kg ha^{-1} when no N fertilizer was applied and 130–138 kg N ha^{-1} when 180 kg N ha^{-1} was applied (Table 9). The N uptake of the hybrid rice at Tuanlin ranged from 62 to 65 kg ha^{-1} in the 0-N treatment, and from 127 to 195 kg ha^{-1} in the 180-N treatment. Nitrogen uptake was significantly affected by the rate of N application, but not by water regime. At TL99 and TL00, increasing the number of splits from two to four or six increased the N uptake significantly. The apparent N recovery at N levels of 180 kg N ha^{-1}, ranged from 0.45 to 0.72 at TL00 and from 0.39 to 0.51 at Muñoz. There was no consistency in the

Table 9. Nitrogen uptake (kg ha^{-1}) at harvest for the three experiments.

N regime (kg ha^{-1})	Tuanlin 1999 CS[a]	Tuanlin 1999 SNS[b]	Tuanlin 2000 CS	Tuanlin 2000 SNS
0	-	-	65 a	62 a
180 (2 splits)	135	127	146 b	156 b
180 (4 splits, early)	167	151	165 bc	162 b
180 (4 splits ’99, 6 splits ’00)	169	155	195 c	177 b

N regime (kg ha^{-1})	Muñoz 2001 CS	Muñoz 2001 SNSv[c]	Muñoz 2001 SNS
0	51 a	59 a	46 a
90	86 b	82 b	87 b
180	131 c	130 c	138 c

Statistical differences (P≤0.05) between N regimes are indicated by different lower-case letter.

[a] CS = continuously submerged.

[b] SNS = alternately submerged-nonsubmerged during the whole cropping season.

[c] SNSv = alternately submerged-nonsubmerged in the vegetative phase only.

effect of water regime on apparent N recovery. The higher apparent N recovery at Tuanlin than at Muñoz could have been caused by the difference between hybrid and inbred cultivars. Yang et al. (1999) reported that hybrid rice has a greater root N-absorption potential than inbred rice.

Conclusions and discussion

One of the main findings in our experiments is that the implementation of a recommended water regime of alternate submergence-nonsubmergence (SNS) with mid-season drainage did not lead to very dry soil conditions during the nonsubmergence periods. Shallow groundwater tables remained within the rooted depth of the soil profile and soil water potentials were never much below –10 kPa (as measured at Muñoz and as inferred from shallow groundwater at Tuanlin). This had the following consequences for the performance of SNS regimes:

- Biomass, yield and yield components were statistically the same under SNS and CS regimes at both sites, at all tested levels of N, and for both the hybrid and inbred rice varieties.
- The amount of water saved with SNS was relatively small: 6–14% of total water input and 15–18% of irrigation water input. There was no significant N by water interaction.

The absence of a yield loss under SNS compared with CS is explained by the relatively wet soil conditions. Wopereis et al. (1996a) extensively investigated the effect of nonsubmerged periods in lowland rice on crop growth and yield formation. They found that leaf expansion stopped when soil water potentials ranged from –50 to –250 kPa, depending on crop age and season. Leaf transpiration rates declined when potentials dropped below –100 kPa. Other growth-reducing processes such as leaf rolling and accelerated leaf death occurred only at potentials below –200 kPa. In our experiments, the lower LAI in SNS than in CS at panicle initiation and flowering at the N level of 180 kg ha^{-1} indicates that leaf expansion was reduced already at soil water potentials of 0 to –10 kPa. Similar findings were obtained by Lu et al. (2000), who reported LAI to be significantly decreased when soil water potential was allowed to drop to –10 kPa under SNS. This reduction, however, did not significantly affect dry matter production and grain yield, just as in our experiments. Finally, Wopereis et al. (1996a) reported that crop development was delayed when the rice crop was water-stressed in both the vegetative and reproductive phase. However, in our experiments, SNS had no effect on crop growth duration compared with CS, indicating that no water stress occurred in SNS regimes.

Percolation rates in our experiments were relatively low with 1 to 4.5 mm d^{-1}, mainly because of the high clay content of the soil and the shallow groundwater tables.

Because of these low rates, total water use (rainfall plus irrigation) under conventional CS treatments was only some 600–960 mm, which is in the low range of values for lowland rice as summarized by Bouman (2001) and Tabbal et al. (2002). The actual amount of water saved with the recommended SNS practice under these conditions is therefore small. However, water saving from SNS can have a significant impact on total volume of water saved when extrapolated to the whole rice ecosystem. In Asia, lowland rice is grown on more than 30% of the irrigated land and accounts for 50% of irrigation water (Barker et al., 1999). Freeing only a small portion of water from rice areas can have large social and environmental effects if this water is used for urban, industrial, or environmental purposes.

The lack of a significant water by N interaction in our experiments may again be explained by the particular hydrological conditions in our fields. During the periods of nonsubmergence, the soil remained close to saturation and therefore conditions for nitrification-denitrification were not very favourable (little aeration only). Moreover, with the low percolation rates at our sites, any nitrate formed was not removed very fast from the soil profile, and probably not much extra N was lost during the nonsubmerged periods. For comparison, in reported experiments on loam to clay-loam soils at Pantnagar, India, percolation rates were relatively high at 13–16 mm d^{-1}, and yields at 120 kg N ha^{-1} did decline under SNS compared with CS (Mishra et al., 1990; Tripathi et al., 1986). This yield decline may have been caused by the faster removal of nitrate from the soil profile compared with the situation in our experiments. Dedicated SNS experiments at different fertilizer N levels are needed on lighter-textured soils with higher percolation rates and deeper groundwater tables to study to what extent the results of our field experiments can be extrapolated to such environments.

The results of our field experiments may be characteristic for many large-scale irrigated lowland rice areas in Asia. Rice is produced on a wide variety of soil types but production occurs predominantly in alluvial lowlands, which have relatively low sand content. Heavy clay soils (> 45% clay) make up around 40% of the land area in rice production, which is higher than sandy soils that account for around 20% (Kyuma, 1978). Moreover, many of these lowland soils are poorly drained (Moormann and Van Breemen, 1978) and groundwater tables may be very shallow such as at our sites because of the extensive and continuous application of irrigation. Cabangon et al. (2001) recently compared the Tuanlin data reported here with data obtained from a comparable field experiment in 1999 and 2000 near Jinhua in the Yangtze River delta, Zhejiang Province, China (29°0′ N, 119°8′ E). They also reported no significant differences in yield between the SNS and CS treatments. Here the soil was a silty loam, N fertilizer levels were 0 and 150 kg N ha^{-1}, the varieties used were hybrids, and the ponded water depths did not drop below 15 cm below the surface during the periods of nonsubmergence. Based on these results and our own analyses, we suggest that SNS saves water in lowland rice production and maintains yield levels as long as ponded water or shallow groundwater levels do not drop below 35 cm below the soil surface. The actual amount of water saved in this way will depend upon the hydrological conditions of the site. We have found 6–14% water savings, but others have reported savings up to 30%, though sometimes with associated yield loss probably because the soil was allowed to dry too much during the nonsubmerged periods (e.g., Bouman and Tuong, 2001; Tabbal et al., 2002). To further extrapolate our research findings and to determine the overall extent and quantity of water that can be saved in rice production in Asia, a hydrological characterization of Asia's major rice growing areas is needed, especially in terms of percolation rate and groundwater table depth. Hydrological and crop growth simulation models can then be applied to explore the effects of different implementations of SNS (frequency and duration of nonsubmerged periods) on yield, water savings, and off-site hydrological implications.

CHAPTER 3

Nitrogen economy and water productivity of lowland rice under water-saving irrigation[1]

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Abstract

Water saving in irrigated lowland rice production is increasingly needed to cope with a decreasing availability of fresh water. We investigated the effect of irrigation regimes on grain yield and nitrogen (N) uptake and recovery, and the effect of N management on water productivity (grain yield / evapotranspiration), WP_{ET}.

Four field experiments were carried out — three summer seasons at Tuanlin (2000–2002), China, and one dry season at Muñoz (2001), Philippines — using a hybrid for Tuanlin and an inbred cultivar for Muñoz. Several water-saving regimes were compared with continuous submergence. N fertilizer was applied at 180 kg ha^{-1} at Tuanlin and at 90 and 180 kg ha^{-1} at Muñoz and compared with a 0-N application.

Grain yield ranged from 4.1 t ha^{-1} at Muñoz in 0-N plots to 9.5 t ha^{-1} at Tuanlin in 2001 with 180 kg N ha^{-1}. Alternately submerged-nonsubmerged regimes showed a 4–6% higher yield than continuous submergence. Other water-saving regimes led to yield reduction. In all seasons, N application significantly increased grain yield largely through an increased biomass and grain number. WP_{ET} was significantly increased by N application in three out of four seasons and under limited water stress ranged from 0.70 to 1.17 in 0-N plots and from 1.27 to 1.66 kg m^3 at 180 kg N ha^{-1}. Water-saving regimes also increased WP_{ET} under non water-stressed conditions compared with continuous submergence. A synthesis of the data of three seasons at Tuanlin showed that biomass and apparent N recovery declined linearly with the duration of the crop growth without submergence.

We concluded that the absence of an effect of water-saving regimes was caused by shallow groundwater tables of < 40 cm depth in 2000–2001 at Tuanlin and at Muñoz, whereas at Tuanlin in 2002 there was water deficit in all treatments caused by a deeper drainage. In irrigation systems with a relatively shallow water table, optimal N management is as important as water-saving irrigation to enhance WP_{ET}.

Keywords: Water savings, lowland rice, water productivity, nitrogen uptake, apparent nitrogen recovery, evapotranspiration.

[1] Field Crops Research (2005) in press.

Introduction

Decreasing availability of good-quality fresh water (Postel, 1997) and population growth necessitate a more efficient water use in irrigated rice production systems in Asia. The high water demand of irrigated lowland rice mainly arises from keeping a permanent layer of water on the field (Guerra et al., 1998). The permanent water layer causes evaporation and seepage and percolation to be higher than in non-flooded fields.

To reduce water use in irrigated lowland rice, water-saving techniques are being developed. These techniques include shorter/no wet land preparation, direct (dry) seeding, and introducing periods of non-submergence (Mao, 1993). Researchers in China (Wu, 1999; Li, 2001; Mao, 1993) found that alternately submerged-nonsubmerged (SNS) field conditions significantly reduced water inputs and increased yields. However, Bouman and Tuong (2001) reported that SNS conditions did reduce water inputs but yields usually declined when soil water potential in the root zone reached −10 to −30 kPa and below.

Under water-short conditions, it has been argued that water productivity, (i.e., the amount of harvested product per unit water use), becomes more important than yield or 'land productivity' (Guerra et al., 1998; Tuong and Bouman, 2003). Water use can be defined as total water input through rainfall and irrigation or as evapotranspiration (ET). Reported values for water productivity in rice based on ET, WP_{ET}, range from 0.4 to 1.6 kg m^{-3} (Tuong and Bouman, 2003; Zwart and Bastiaanssen, 2004), suggesting scope for improvement in crop and water management and cultivar selection for higher assimilation/transpiration rates (Peng et al., 1998).

Photosynthetic rates depend on leaf N concentration (Peng et al., 1995; Hasegawa and Horie, 1996; Sheehy et al., 1998) and play a crucial role in biomass production and yield formation. Enhanced leaf growth will lead to increased transpiration and to decreased evaporation through increased shading of the soil.

Current N-fertilizer recommendations for rice in Asia have generally been established under continuously submerged conditions. The adoption of SNS-based technologies could change N dynamics and stimulate N losses (Sah and Mikkelsen, 1983; Eriksen et al., 1985). However, some researchers reported no increase in N losses under SNS conditions (Maeda and Onikura, 1976; Manguiat and Broadbent, 1977; Fillery and Vlek, 1982). Most of these results were obtained in pot experiments, and the interaction between water and N has been little studied under field conditions (Guerra et al., 1998). With the development and introduction of SNS-based water-saving practices, there is a need to re-evaluate the N economy of rice fields.

In this research, we studied crop growth and development, N economy and WP_{ET} under continuous submergence, SNS regimes, and modifications of SNS regimes. The study aims at increasing insight into how nitrogen and water management interact and how they can be improved to increase yield and WP_{ET}.

Materials and methods

Four field experiments were conducted in irrigated lowland rice areas. Three experiments were located at Tuanlin (30°52′ N, 112°11′ E), Hubei Province, China, at an altitude of 100 m, and were conducted in the summer seasons in 2000 (TL00), 2001 (TL01), and 2002 (TL02). The fourth experiment was carried out at the experimental farm of the Philippine Rice Research Institute (PhilRice) at Muñoz (15°40′ N, 120°54′ E), Nueva Ecija Province, Philippines, at an altitude of 35 m, in the dry season of 2001 (MU01). The experimental site at Tuanlin was a farmer's field surrounded by lowland rice fields within the 160,000 ha Zhanghe Irrigation System (see Loeve et al. (2004) for more details of the area). The experimental farm at Muñoz was surrounded by lowland rice fields in the 100,000 ha Upper Pampanga River Integrated Irrigation System (see Tabbal et al. (2002) and Hafeez (2003) for more details of the area).

At both Tuanlin and Muñoz, the soil texture was silty clay loam. At Tuanlin, the hybrid cultivar 2You725 was sown in April and harvested early September. At Muñoz, the tropical inbred cultivar IR72 was sown in late December and harvested in April. Following local practices, seedlings were transplanted at 20 × 20-cm spacing with 3–5 plants per hill. Seedling age at transplanting was 38, 44, 41, and 21 days at TL00, TL01, TL02, and MU01, respectively. Calculations with the rice growth simulation model ORYZA2000 (Bouman et al., 2001), showed that the seedlings were transplanted at almost the same development stage in all four seasons. Plots were regularly hand-weeded and pesticides were used to prevent insect and pest damage. No noticeable crop damage was observed in the experiments.

The experiments were laid out in a split-plot design with water regime as the main block and nitrogen treatments as sub-blocks with four replicates except for TL01, which had only three replicates. All main blocks could be drained independently. Drains around the main blocks were 30 cm deep at TL00, TL01, and MU01, whereas at TL02, the drains were 100 cm deep.

Water treatments

The water regimes tested are listed in Table 1. The water treatment 'alternately submerged/nonsubmerged' (SNS) was included in all four experiments. In SNS, the fields were kept flooded the first 10 days after transplanting and then re-irrigated 3−5 days after the end of standing water. A relatively long period of 10−12 days without ponded water was imposed just before panicle initiation (PI), which is termed 'mid-season drainage' (Mao, 1993). Since no big difference was found between SNS and

Table 1. Total irrigation water input (mm) depending on water regime in three experiments at Tuanlin, China, and one experiment at Muñoz, Philippines, 2000-2002.

Water regime	Tuanlin			Muñoz
	2000	2001	2002	2001
Continuously submerged	415	-	-	511
Alternately submerged/nonsubmerged:				
Throughout season with MSD[a]	339	533	1216	427
Vegetative phase only	-	-	-	489
Re-irrigation at SWP[b] = −30kPa (FI-30)	-	-	492	-
Re-irrigation at SWP = −50kPa (FI-50)	-	-	470	-
Flush irrigation	-	53	-	-
Partially rainfed	-	89	-	-
Raised beds	-	357	-	-

[a] MSD=mid-season drainage

[b] SWP=soil water potential (FI=flush irrigation).

continuous submergence at Tuanlin in grain yield and biomass (Chapter 2; Belder et al., 2004), the continuously submerged regime was omitted in 2001 and 2002. In these years, different modifications of SNS were tested such as flush irrigation and raised beds. In flush irrigation, irrigation water was based on the occurrence of cracks in the soil. Also a partially rainfed regime was tested at TL01, in which the fields were only irrigated straight after fertilizer applications. Raised beds were 90 cm wide containing 5 rows at 20 cm distance. Width and depth of the furrows were 30 cm. In the raised bed system, plots were re-irrigated when water in the furrows had disappeared. At TL02, besides the SNS regime, plots were flush irrigated when soil water potential reached −30 kPa (FI-30) or −50 kPa (FI-50). Soil water potential was measured with tensiometers at 15-cm depth.

Land preparation consisted of wet tillage followed by harrowing, a process referred to as ‘puddling’. Puddling is practiced to create a semi-impermeable layer (hardpan) and to ease transplanting. Land preparation in raised bed and flush irrigation regimes at TL01 and in FI-30 and FI-50 at TL02 was done under dry soil conditions and no puddled layer was created. Dry land preparation can save water under specific conditions (Tabbal et al., 2002) and allows roots to grow deeper than the broken hardpan, which is commonly found at around 15−30 cm depth.

To prevent seepage between plots with different water regimes, plastic sheets were installed in the bunds down to a depth of 40 cm at both locations. This was well below the top of the hardpan, which was about 20 cm deep at both locations.

Nitrogen treatments

Levels of N fertilizer were 0 and 180 kg ha^{-1} at TL00, TL01, and TL02. At Muñoz, an intermediate level of 90 kg N ha^{-1} was included. At Tuanlin, 180 kg N ha^{-1} was applied as urea in four splits: 30% basal, 30% 10 days after transplanting (DAT), 30% at PI, and 10% at flowering. At Muñoz, the 90 and 180 kg urea-N ha^{-1} were split as follows: 22% basal, 28% 25 DAT, 33% at PI, and 17% at flowering. At TL00, two other N splits were tested. One treatment followed the common farmers' practice (50% basal and 50% 10 DAT) and, in the other, N was applied as 17% basal, 20% 16 DAT, 27% at mid-tillering, and 36% at PI.

P and K were applied as basal dressings in all treatments. P was applied at 25 kg ha^{-1} at TL00, 70 kg ha^{-1} at TL01 and TL02, and 30 kg ha^{-1} at Muñoz. K was applied at 70 kg ha^{-1} at TL00–02 and at 100 kg ha^{-1} at Muñoz. All basal fertilizers were incorporated in the soil at the last harrowing one day before transplanting.

Measurements

Daily weather data were collected from weather stations at the sites, and included rainfall, solar radiation, wind speed, vapour pressure, and air temperature. Crop samples to determine biomass, plant N content, and leaf area index (LAI) at Tuanlin were taken five times in 2000 and four times in 2001 and 2002. Samples at TL00 were taken at 17 DAT, 29 DAT, 57 DAT (PI), 82 DAT (flowering), and 109–113 DAT (physiological maturity). The four samplings at TL01 and TL02 were taken at 15 DAT, PI, flowering, and physiological maturity. At Muñoz, the crop was sampled seven times at 0, 14, 28, 41 (PI), 62 (flowering), 76, and 90–95 DAT (physiological maturity). At each sampling, all plants of 12 hills per plot (representing 0.48 m^2) were pulled out, washed, and processed. At Muñoz, 100 seedlings were sampled at transplanting. Biomass of the above-ground plant parts was determined after drying at 70 °C to constant weight. Grain yield was determined from a central 4.8- and 6.0-m^2 area at Tuanlin and Muñoz, respectively, and was expressed at 14% moisture content. Biomass at physiological maturity was derived from this central area by using the harvest index from the 12-hill sample. At Tuanlin, the N content of plant material was determined using the micro-Kjeldahl method (Bremner and Mulvaney, 1982), whereas at Muñoz, the Dumas-method as described by Bergersen (1980) was used.

At both sites, the amounts of irrigation and drainage water were measured throughout the growing season. The amount of irrigation water was determined using flow meters installed in the irrigation pipes at Tuanlin and using cut-throat flumes and V-notch weirs in the irrigation channels at Muñoz. At Tuanlin, ponded water depth was measured in each subplot with perforated tubes of 30-cm height that could record both above-ground and below-ground water level. During periods of nonsubmergence, the ponded water level dropped below the soil surface and was recorded as 'negative ponded water depth'. At Muñoz, the ponded water depth was measured with sloping gauges that could not record negative (below surface) values. To record the shallow groundwater dynamics at both sites, six plastic tubes of 1.75-m depth that were perforated 50 cm from the top downward, were installed in the bunds between each replicate. The water level recorded in these tubes is referred to as 'groundwater depth'.

Calculations and analyses

Evaporation (E) and transpiration (T) were calculated with the ORYZA2000 model (Bouman et al., 2001) using the adjusted Penman (1948) method and the measured weather data. Separation of the calculated reference evapotranspiration over E and T was based on the measured and daily interpolated leaf area indices, LAI (ha leaf ha^{-1} soil), using exponential extinction of radiation through a canopy (Van Laar et al., 1997):

$$T = ET_{rd}\,(1 - \exp(-k \times LAI)) + ET_{ae} \times LAI \qquad (\text{mm d}^{-1}) \qquad (1)$$

$$E = (ET_{rd} + ET_{ae})\,\exp(-k \times LAI) \qquad (\text{mm d}^{-1}) \qquad (2)$$

where ET_{rd} and ET_{ae} are the radiation and drying power terms of the reference evapotranspiration and k is the extinction coefficient for solar radiation (a value of 0.5 was used).

Actual transpiration rates were assumed to be potential since the soil water potentials in the root zone did not drop below −70 kPa (Wopereis et al., 1996a). Actual evaporation rates were assumed to be the same as potential values when the soil was submerged or saturated, and dropped with decreasing soil moisture content during nonsubmerged days (see Bouman et al., 2001 for calculation details).

Water productivity with respect to evapotranspiration (the sum of calculated E and T, see above), WP_{ET}, was calculated as

$$WP_{ET} = \frac{\text{grain yield}}{\sum ET} \qquad (\text{kg grain m}^{-3}\text{ water}) \qquad (3)$$

where grain yield is in kg ha^{-1} and $\sum ET$ is evapotranspiration in m^3 ha^{-1}.

The apparent N recovery (ANR) in kg kg^{-1} was calculated as the total above-ground plant N in fertilized plots minus the total plant N in unfertilized plots divided by the N application rate. Internal N use efficiency (INUE) was calculated as grain yield divided by total plant N (Witt et al., 1999). Agronomic N use efficiency ANUE (kg yield per kg N applied) was calculated as:

$$ANUE = \frac{\text{grain yield}_{\text{fertilized}} - \text{grain yield}_{\text{unfertilized}}}{\text{N application rate}} \qquad (4)$$

where N application rate, total plant N, and grain yield are expressed in kg ha^{-1}.

N dilution curves were estimated according to Greenwood et al. (1990) as validated for rice by Sheehy et al. (1998):

$$N\% = a\, W^{-b} \qquad (W \geq 1 \text{ t ha}^{-1}) \qquad (5)$$

where a and b are dimensionless parameters and W is biomass (t ha^{-1}). The a and b parameters were derived from iterative non-linear least-square regression using the DUD method (Ralston and Jenrich, 1979) as implemented in the PROC NLIN (a procedure to run a regression) of the SAS software package (SAS Institute Inc., 1988). Analysis of variance was performed with water as the main factor and N regime as the sub-factor. Levels of significance are indicated by $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$.

Results and discussion

Weather

Rainfall from transplanting to harvest was 448 mm in 2000, 297 mm in 2001, and 368 mm in 2002 at Tuanlin, and 86 mm at Muñoz in 2001. Average rainfall for the preceding ten years (1990–1999) was 556 mm at Tuanlin and 51 mm at Muñoz. At Tuanlin, the rainfall distribution differed among years with an early wet season in 2002, and a wet August in 2000 (Table 2, Figure 1). Temperatures at Tuanlin were highest in July, while temperatures in the dry season at Muñoz gradually increased from sowing to physiological maturity. Average air temperatures in the four experiments ranged from 26.6 to 27.1 °C. Average daily solar radiation from transplanting till physiological maturity was 19.7 MJ m^{-2} d^{-1} at TL00, 20.5 MJ m^{-2} d^{-1} at TL01, 19.5 MJ m^{-2} d^{-1} at TL02, and 20.6 MJ m^{-2} d^{-1} at MU01. Average wind speed was higher at Muñoz, with 2.1 m s^{-1} on average compared with 1.2–1.5 m s^{-1} at Tuanlin. Average daily vapour pressure deficit ranged from 0.9 to 1.2 kPa.

Ponded water and groundwater depths

Water levels of several water regimes are presented with rainfall distribution in Figure 1. Rainfall and irrigation (not shown) events caused the ponded water depths to rise. Above and below groundwater tables in raised bed and flush irrigation at TL01 were nearly the same as in the partially rainfed regime and were therefore omitted. Likewise FI-50 at TL02 represents the water depth for the FI-30 treatment since there was hardly any difference in water depths between the two treatments.

Water levels in continuously submerged plots at TL00 and MU01 were above the soil surface until shortly before physiological maturity. All other water regimes had periods without submergence varying from 3–10 days at TL00 and MU01 to 20 days

Table 2. Monthly cumulative rainfall and incoming radiation and monthly averages of maximum (T max) and minimum (T min) air temperature, wind speed, and vapour pressure deficit.

Month	Rainfall	Radiation	T max	T min	Wind speed	Vapour pressure deficit
	(mm)	(MJ m^{-2} d^{-1})	(°C)	(°C)	(m s^{-1})	(kPa)
Tuanlin 2000						
May	101	21.1	28.4	18.2	1.0	1.38
June	49	20.6	30.1	20.2	1.6	1.26
July	112	20.3	32.3	26.3	1.0	1.04
August	186	20.2	31.1	23.7	1.2	1.14
September	-	17.8	26.7	18.8	1.7	1.04
Tuanlin 2001						
May	50	20.2	28.4	17.5	0.9	0.99
June	70	20.1	29.1	22.5	1.2	0.78
July	101	22.8	33.4	25.4	1.4	1.16
August	103	19.8	31.0	23.3	1.4	1.07
September	0	21.2	29.5	20.4	1.5	1.14
Tuanlin 2002						
May	196	16.7	23.2	16.4	0.9	0.62
June	174	20.2	30.6	23.7	1.1	0.95
July	110	20.8	31.8	24.6	1.5	1.03
August	61	18.8	30.5	23.0	1.3	0.88
September	14	17.6	28.1	18.8	2.0	0.88
Muñoz 2001						
January	19	19.7	30.3	22.8	3.3	1.05
February	24	17.3	30.2	22.5	2.6	0.85
March	30	21.0	31.3	22.7	1.8	0.83
April	29	22.4	34.2	24.1	1.2	1.04

at TL02. Although irrigation applications were more frequent and the total amount of irrigation was 2.3–3.6 times higher at TL02 than at TL00 and TL01 in the SNS regime (Table 1), field submergence was hardly feasible half way between PI and flowering, because of the deep drains.

The groundwater depths (Figure 2) show that subsurface hydrology at TL02 differed from the other three experiments. At TL01 and MU01, the groundwater was mostly not deeper than 40 cm below the soil surface until final drainage. At TL02 with

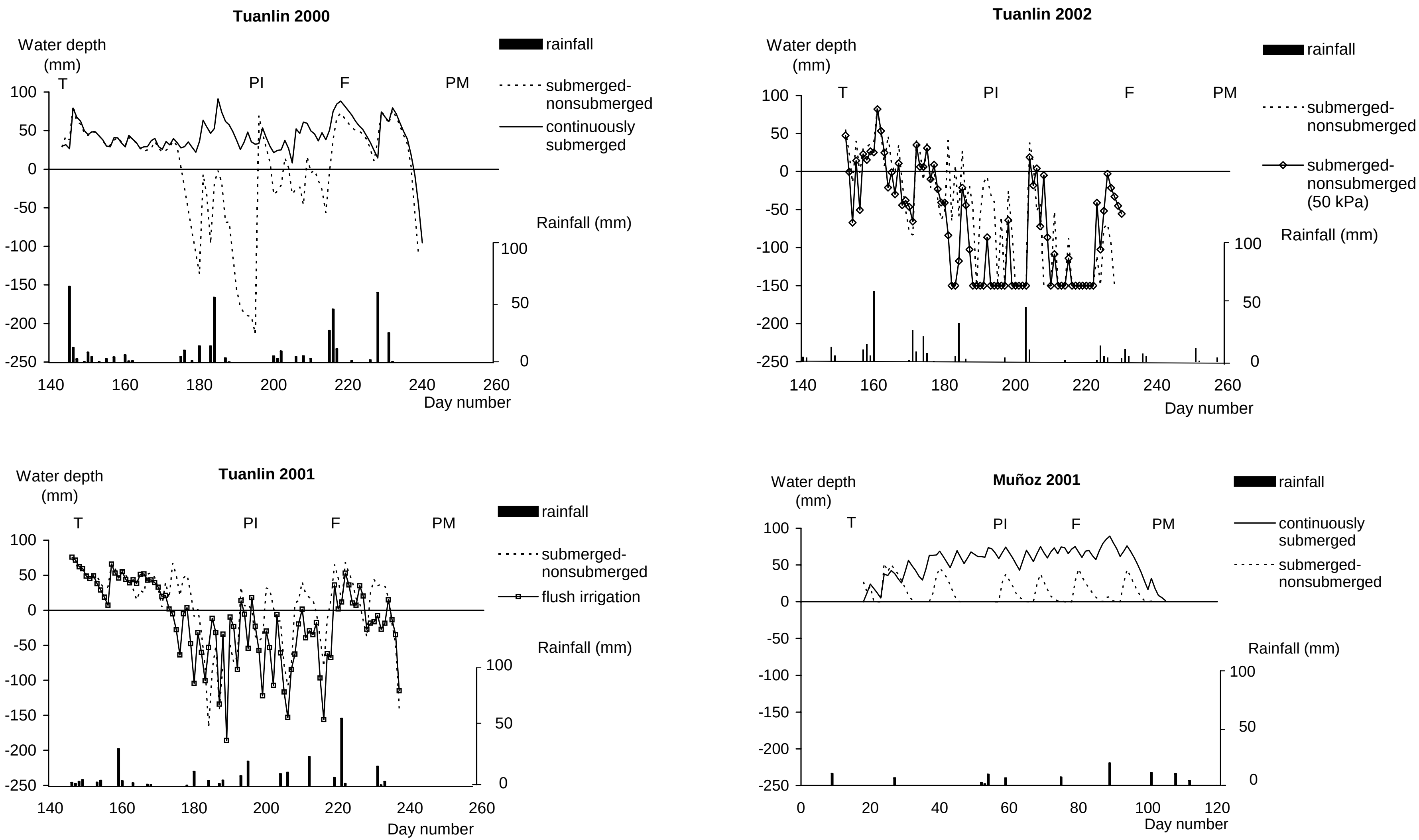

Figure 1. Water depth (mm) and rainfall distribution at Tuanlin (China) and Muñoz (Philippines), 2000–2002. When the water depth fell below the depth of the measuring device, values were set at a constant (–150 mm at Tuanlin in 2002 and 0 mm at Muñoz). T=transplanting, PI=panicle initiation, F=flowering, PM=physiological maturity.

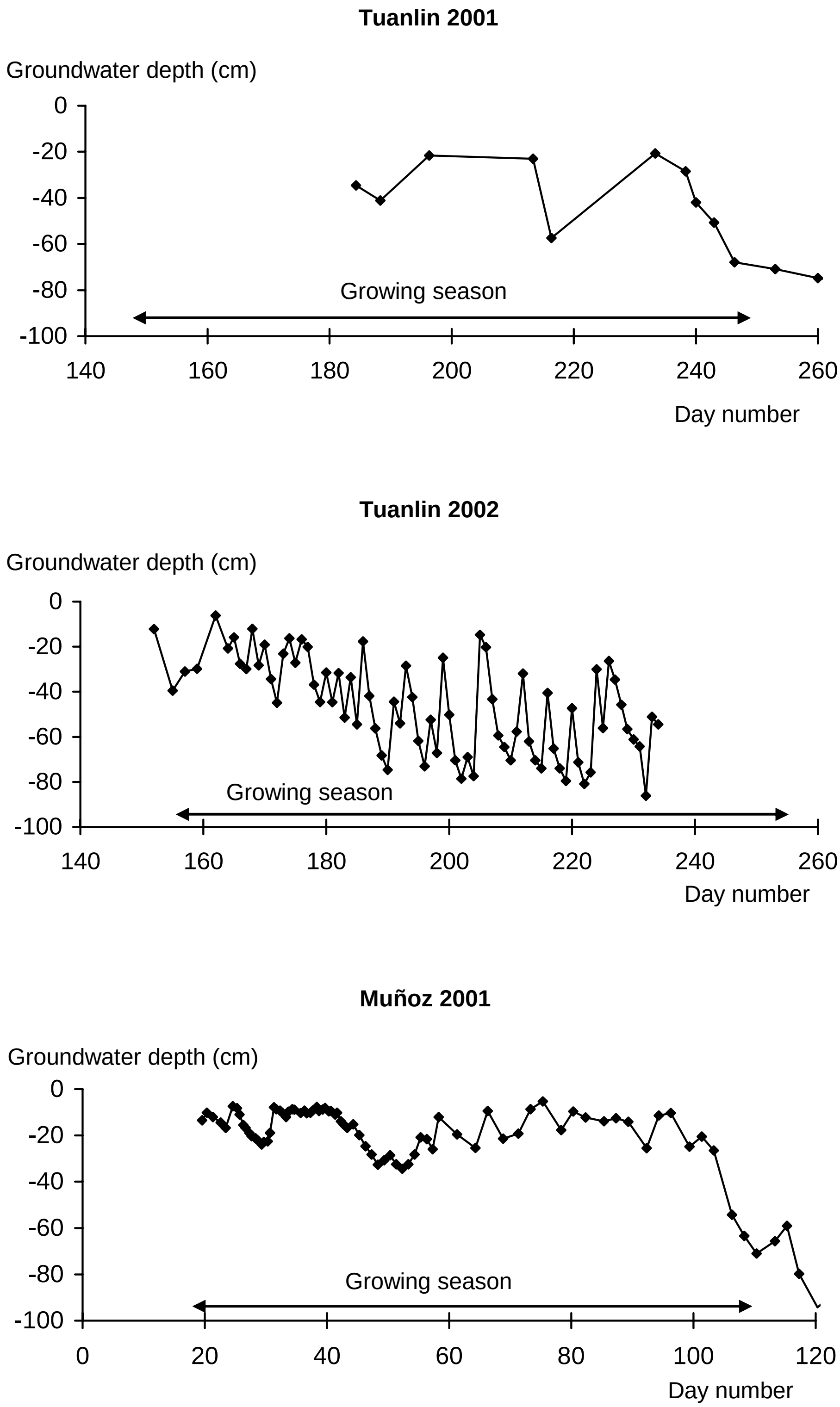

Figure 2. Depth of shallow groundwater table (cm) at Tuanlin (China) and Muñoz (Philippines), 2001–2002.

the deeper drains, the groundwater fluctuated between soil surface and −80 cm throughout the season.

Transpiration and evaporation

Seasonal transpiration ranged from 169 to 518 mm and strongly depended on N level but little on water regime (Table 3). The range in total transpiration also reflects differences in observed LAI and length of the growing season. The inbred cultivar at Muñoz had a shorter growth duration and lower LAI values (maximum 5.3) compared with the hybrid cultivar (maximum LAI of 6.3−11.5) used at Tuanlin, thereby resulting in less transpiration. The application of fertilizer N increased leaf area growth, and, as a consequence, increased the amount of transpiration. The highest calculated daily transpiration rate was 7.4 mm d^{-1} at TL00. Transpiration was only reduced by a maximum of 6% under SNS as compared with continuous submergence caused by a reduced leaf growth rate.

Seasonal evaporation ranged from 112 to 318 mm and showed a significant reduction with increased amounts of N. The application of N stimulated leaf growth, which led to more light interception and less light transmission to the soil surface, resulting in reduced evaporation. Introducing periods of non-submergence reduced evaporation in 0-N plots by 2–33%, while the effect of non-submergence on evaporation was smaller or absent in 180-N plots. At Muñoz, application of 180 kg N ha^{-1} caused evaporation to be 56% lower than at 0-N, because the relative effect of the LAI increase was greater than at Tuanlin. Higher wind speeds and lower LAI values at Muñoz caused evaporation to be higher than at Tuanlin.

The fraction T of ET was always higher in fertilized plots than in unfertilized plots, and ranged from 0.59 to 0.71 in 0-N plots and from 0.78 to 0.84 in 180-N plots. At comparable N levels, T/ET values were lower at Muñoz than at Tuanlin because of lower LAI values and higher wind speeds at the time of incomplete canopy closure.

Grain yield

Grain yields ranged from 4.08 to 9.54 t ha^{-1} (Table 4) and strongly responded to N application in three out of four seasons. Application of 180 kg N ha^{-1} at Tuanlin resulted in grain yield increase of 3.91 t ha^{-1} at TL00, 4.32 t ha^{-1} at TL01, and 0.04 t ha^{-1} at TL02, respectively. At TL02, severe water stress eliminated a positive effect of N. At Muñoz, applying 180 kg N ha^{-1} led to an increase in grain yield of 3.55 t ha^{-1}. Water as main factor did not significantly affect yield within seasons and there were no significant water × N interactions (Table 5). Pair-wise comparison showed significant differences at 180 kg N ha^{-1}. In 2001, SNS had a significant higher grain yield (9.54 t ha^{-1}) than the other three regimes. In the same year, the raised bed treat-

Table 3. Calculated seasonal transpiration and evaporation at Tuanlin (China) 2000-2002 and at Muñoz (Philippines) 2001.

Experiment	Water regime	N rate ($kg\ ha^{-1}$)	Transpiration (mm)	Evaporation (mm)
Tuanlin 2000				
	Continuously submerged	0	384 ± 17	246 ± 17
	Continuously submerged	180 [a]	518 ± 4	113 ± 4
	Continuously submerged	180 [b]	507 ± 7	130 ± 6
	Continuously submerged	180 [c]	507 ± 5	131 ± 5
	Submerged-nonsubmerged	0	353 ± 20	241 ± 15
	Submerged-nonsubmerged	180 [a]	504 ± 9	116 ± 9
	Submerged-nonsubmerged	180 [b]	503 ± 3	131 ± 3
	Submerged-nonsubmerged	180 [c]	509 ± 6	126 ± 5
	Submerged-nonsubmerged –30	180	470 ± 8	112 ± 8
	Submerged-nonsubmerged –50[e]	0	376 ± 9	176 ± 5
	Submerged-nonsubmerged –50	180	467 ± 1	117 ± 1
Muñoz 2001				
	Continuously submerged	0	169 ± 9	318 ± 7
	Continuously submerged	90	289 ± 24	220 ± 22
	Continuously submerged	180	353 ± 10	162 ± 10
	Submerged-nonsubmerged (veg)[f]	0	214 ± 39	212 ± 27
	Submerged-nonsubmerged (veg)	90	290 ± 14	169 ± 11
	Submerged-nonsubmerged (veg)	180	337 ± 14	128 ± 8
	Submerged-nonsubmerged	0	190 ± 35	249 ± 26
	Submerged-nonsubmerged	90	292 ± 15	181 ± 10
	Submerged-nonsubmerged	180	335 ± 5	143 ± 4

[a] N applied in two splits: 50% basal and 50% 10 days after transplanting;

[b] N applied as 30% basal, 30% 10 days after transplanting, 30% at PI, and 10% at flowering;

[c] N applied as 17% basal, 20% 16 days after transplanting, 27% at mid-tillering, and 36% at PI;

[d] alternately submerged-nonsubmerged, re-irrigation when soil water potential at 20 cm reaches −30kPa;

[e] alternately submerged-nonsubmerged, re-irrigation when soil water potential at 20-cm reaches −50kPa;

[f] alternately submerged-nonsubmerged in vegetative phase only.

ment had a significant lower grain yield than the other three water treatments. At Muñoz, the water-saving regimes had a significant higher grain yield than the continuously submerged regime. Also at TL00 did SNS lead to an increase in grain yield, but the difference was not significant in comparison with continuous submergence. In general, high response to N application occurred under non water-stressed conditions, whereas water stress reduced response to N application to a large extent.

Crop growth and development

Total biomass at physiological maturity was as high as 17.3 t ha^{-1} at TL00 at 180 kg N ha^{-1}, and as low as 7.8 t ha^{-1} at MU01 with 0-N (Figure 3). Crop leaf growth responded strongly to N fertilizations which was reflected in the biomass increase. At Tuanlin, biomass was high in 2000 and 2001 and responded well to N applications. In 2002, biomass was lower and the N response was weak. Allowing water potentials at 15 cm depth to reach values down to −30 and −50 kPa, resulted in water stress as was also found by Wopereis et al. (1996a). Since no statistical difference was found between SNS −30 and −50 kPa and the SNS control treatment, we conclude that also the SNS regime suffered water stress.

Biomass accumulation during the vegetative phase (until PI) was much lower for the inbred cultivar at Muñoz than for the hybrid cultivar at Tuanlin. In the hybrid cultivar at TL01, biomass at PI was 51% of the final biomass and at TL02 it was 46%. For the inbred cultivar at MU01, biomass at PI was only 29% of the final biomass. This difference can be partly explained by a higher temperature sum of the hybrid cultivar to reach PI, and the lower temperatures at Tuanlin during the vegetative stage.

Linear relationships ($R^2 \geq 0.47$) between biomass at PI and the number of grains at harvest were found for the hybrid at Tuanlin and for the inbred at Muñoz. The relationships for TL01 and MU01 are presented in Figure 4. Similar relationships with lower coefficients of determination ($R^2 \geq 0.37$) were established between biomass at flowering and grain number. Kropff et al. (1994) reported a good correlation between spikelet density and biomass accumulation between PI and flowering and used this relationship in the crop growth model ORYZA1. In our data set, the correlation between biomass increase between PI and flowering and grain number was weaker than with biomass at either PI or flowering, due to variation in the assessment of the PI stage.

Water productivity and water use efficiency

In three out of four experiments, N application significantly increased water productivity (WP_{ET}) (Tables 4 and 5). In 0-N plots, WP_{ET} ranged from 0.70 to 1.20 kg m^{-3} while in 180-N plots, WP_{ET} ranged from 1.15 to 1.66 kg m^{-3} (Table 4). Values of

Table 4. Grain yield, water productivity, apparent N recovery, internal N use efficiency, and agronomic N use efficiency at Tuanlin (China) 2000-2002, and at Muñoz, Philippines 2001.

Experiment	Water regime	N level ($kg\ ha^{-1}$)	Grain yield ($kg\ ha^{-1}$)	Water productivity ($kg\ m^{-3}$)	Apparent N recovery ($kg\ kg^{-1}$)	Internal N use efficiency (kg grain kg plant N^{-1})	Agronomic N use efficiency (Δ kg grain kg N $applied^{-1}$)
Tuanlin							
2000	Continuously submerged	0	4.42 ± 0.30	0.70 ± 0.05		61 ± 2	
	Continuously submerged	180 [a]	8.23 ± 0.25	1.30 ± 0.04	0.45 ±0.09	51 ± 4	21.1 ±0.4
	Continuously submerged	180 [b]	8.10 ± 0.38	1.27 ± 0.06	0.55 ±0.03	44 ± 3	20.4 ±0.5
	Continuously submerged	180 [c]	8.67 ± 0.31	1.36 ± 0.05	0.72 ±0.05	40 ± 2	23.6 ±1.6
	Submerged-nonsubmerged	0	4.71 ± 0.55	0.79 ± 0.09		64 ± 3	
	Submerged-nonsubmerged	180 [a]	8.94 ± 0.13	1.44 ± 0.02	0.52 ±0.09	52 ± 5	23.5 ±3.6
	Submerged-nonsubmerged	180 [b]	8.46 ± 0.38	1.33 ± 0.06	0.56 ±0.01	46 ± 2	20.8 ±5.2
	Submerged-nonsubmerged	180 [c]	8.46 ± 0.14	1.33 ± 0.02	0.64 ±0.13	45 ± 5	20.8 ±3.3
2001	Submerged-nonsubmerged	0	5.22 ± 0.39	0.89 ± 0.06		57 ± 5	
	Submerged-nonsubmerged	180	9.54 ± 0.31	1.57 ± 0.05	0.43 ±0.03	52 ± 1	24.0 ±3.0
	Partially rainfed	0	5.05 ± 0.29	0.98 ± 0.05		68 ± 0	
	Partially rainfed	180	8.75 ± 0.20	1.48 ± 0.03	0.41 ±0.05	56 ± 3	20.6 ±2.6
	Flush irrigation	0	4.86 ± 0.24	0.93 ± 0.04		61 ± 4	
	Flush irrigation	180	8.76 ± 0.54	1.51 ± 0.11	0.53 ±0.04	46 ± 2	21.6 ±3.5
	Raised bed	0	5.44 ± 0.35	1.04 ± 0.06		61 ± 2	
	Raised bed	180	8.18 ± 0.08	1.43 ± 0.01	0.29 ±0.03	55 ± 2	15.2 ±1.6

Table 4. Continued.

2002	Submerged-nonsubmerged	0	6.7 ± 0.21	1.20 ± 0.02		66 ± 5	
	Submerged-nonsubmerged	180	6.7 ± 0.34	1.16 ± 0.06	0.21 ± 0.02	46 ± 3	0.2 ± 2.4
	Submerged-nonsubmerged –30[d]	0	5.9 ± 0.30	1.08 ± 0.05		65 ± 4	
	Submerged-nonsubmerged –30	180	6.6 ± 0.49	1.15 ± 0.08	0.31 ± 0.04	43 ± 4	4.1 ± 1.1
	Submerged-nonsubmerged –50[e]	0	5.7 ± 0.51	1.04 ± 0.09		66 ± 3	
	Submerged-nonsubmerged –50	180	6.6 ± 0.29	1.15 ± 0.05	0.30 ± 0.06	46 ± 3	5.4 ± 3.0
Muñoz							
2001	Continuously submerged	0	4.35 ± 0.22	0.89 ± 0.04		76 ± 3	
	Continuously submerged	90	6.68 ± 0.34	1.31 ± 0.07	0.39 ± 0.10	69 ± 2	25.9 ± 2.3
	Continuously submerged	180	7.16 ± 0.25	1.39 ± 0.05	0.44 ± 0.07	50 ± 7	15.6 ± 2.0
	Submerged-nonsubmerged (veg)[f]	0	5.04 ± 0.82	1.17 ± 0.16		77 ± 5	
	Submerged-nonsubmerged (veg)	90	6.69 ± 0.13	1.46 ± 0.04	0.26 ± 0.05	72 ± 3	18.4 ± 9.7
	Submerged-nonsubmerged (veg)	180	7.72 ± 0.11	1.66 ± 0.01	0.40 ± 0.05	53 ± 3	14.9 ± 4.2
	Submerged-nonsubmerged	0	4.08 ± 0.32	0.92 ± 0.14		80 ± 2	
	Submerged-nonsubmerged	90	6.39 ± 0.19	1.35 ± 0.04	0.46 ± 0.07	66 ± 3	25.7 ± 6.4
	Submerged-nonsubmerged	180	7.63 ± 0.19	1.60 ± 0.04	0.51 ± 0.09	50 ± 4	19.8 ± 3.1

[a] N applied in two splits: 50% basal and 50% 10 days after transplanting.
[b] N applied as 30% basal, 30% 10 days after transplanting, 30% at panicle initiation, and 10% at flowering.
[c] N applied as 17% basal, 20% 16 days after transplanting, 27% at mid-tillering, and 36% at panicle initiation.
[d] alternately submerged-nonsubmerged, re-irrigation when soil water potential at 20 cm reaches −30kPa.
[e] alternately submerged-nonsubmerged, re-irrigation when soil water potential at 20 cm reaches −50kPa.
[f] alternately submerged-nonsubmerged in vegetative phase only.

Table 5. Analysis of variance for water productivity (WP_{ET}), grain yield, total dry matter, plant N, and apparent N recovery at physiological maturity of rice.

Experiment	Factor	df[a]	WP_{ET} ($kg\ m^{-3}$)	Grain yield ($kg\ ha^{-1}$)	Total above-ground dry matter ($kg\ ha^{-1}$)	Total plant N ($kg\ ha^{-1}$)	Apparent N recovery ($kg\ kg^{-1}$)	Internal N use efficiency (kg grain kg^{-1} plant N)	Agronomic N use efficiency (kg yield kg^{-1} N applied)
Tuanlin 2000	water[b]	1	ns	ns	ns	ns	ns	ns	ns
	N level[b]	1	***	***	***	***	-	***	-
	water × N level[b]	1	ns	ns	ns	ns	-	ns	-
	N timing	2	ns	ns	ns	*	*	*	ns
	water × N timing	2	ns	ns	ns	ns	ns	ns	ns
Tuanlin 2001	water	3	ns	ns	*	ns	*	ns	*
	N level	1	***	***	***	***	-	***	-
	water × N level	3	ns	ns	ns	ns	-	ns	-
Tuanlin 2002	water	2	ns	ns	ns	ns	ns	ns	ns
	N level	1	ns	*	**	***	-	***	-
	water × N level	2	ns	ns	ns	ns	-	ns	-
Muñoz 2001	water	2	*	ns	ns	ns	*	ns	ns
	N level[c]	2	***	***	***	***	*	***	*
	water × N level	4	ns	ns	ns	ns	ns	ns	ns

ns = not significant
[a] degrees of freedom
[b] averages of 3 splits

* $P<0.05$
** $P<0.01$
*** $P<0.001$

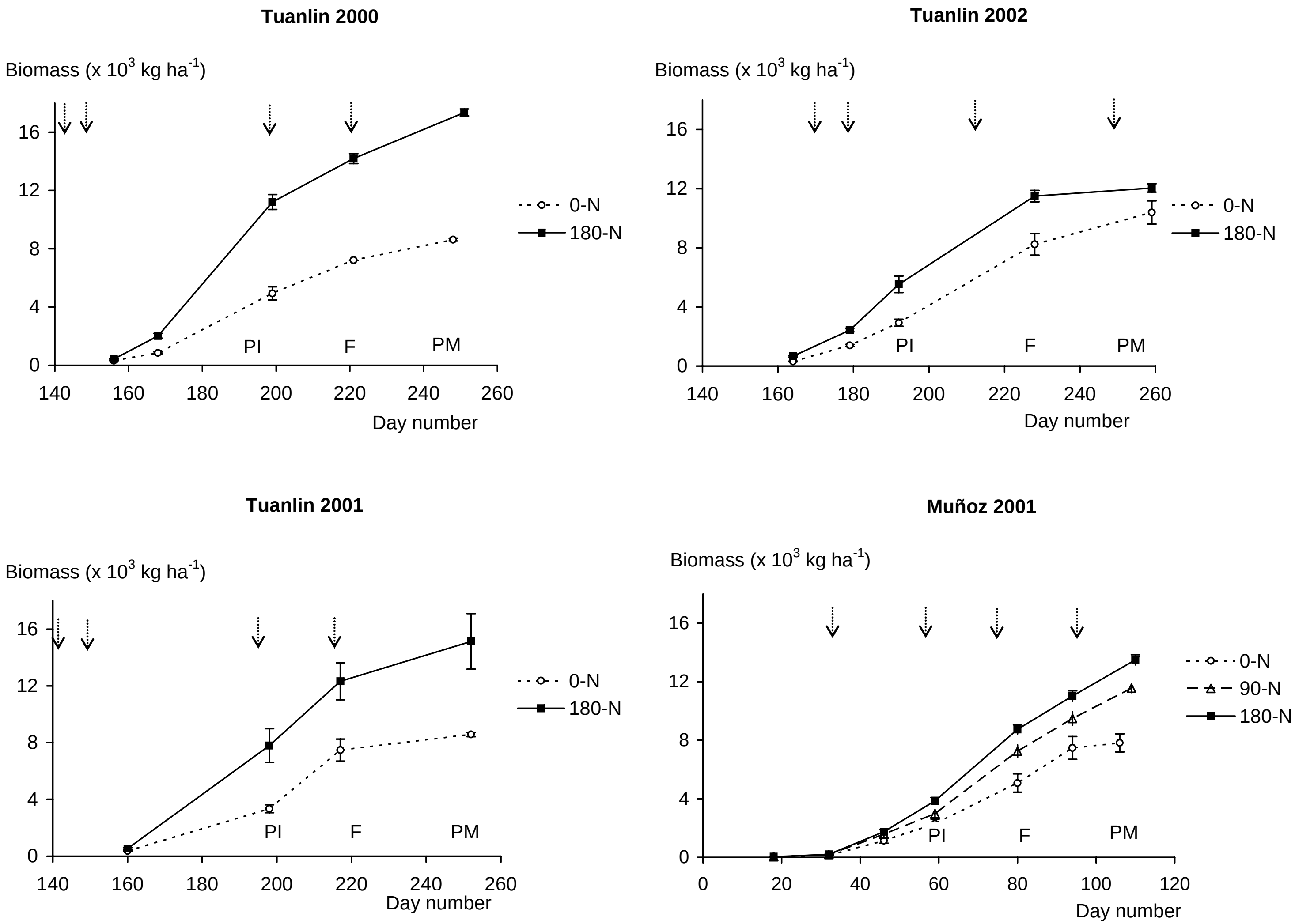

Figure 3. Total above-ground biomass during the rice-cropping season in treatments receiving 0 and 180 kg N ha^{-1} at Tuanlin (China) and Muñoz (Philippines), 2000–2002, averaged over water regimes; arrows indicate fertilizer N applications; PI=panicle initiation, F=flowering, PM=physiological maturity.

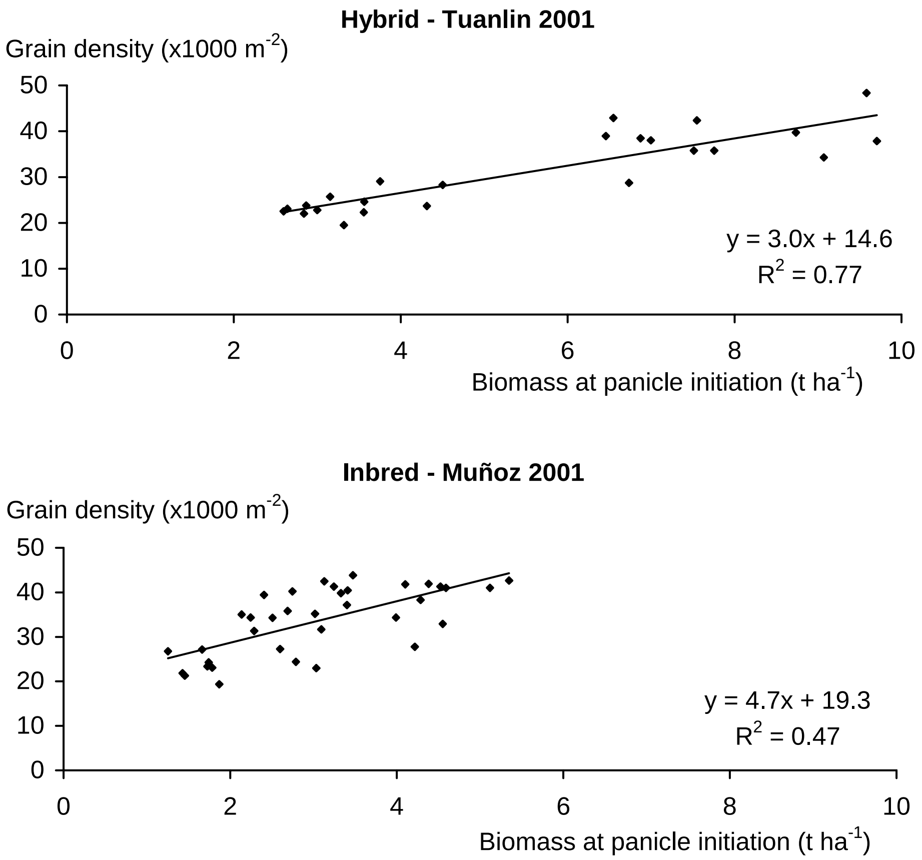

Figure 4. Grain density versus total above-ground biomass at PI for the hybrid cultivar at Tuanlin (China) in 2001 and for the inbred cultivar at Muñoz (Philippines) in 2001. Dots are measured data and lines are regression curves.

WP_{ET} were in the range reported by Tuong and Bouman (2003) and Zwart and Bastiaanssen (2004). Differences between seasons at Tuanlin mainly followed the trends in differences in grain yield. At 180-N, WP_{ET} was 4–20% higher under SNS regimes than under continuous submergence. There was only a small range of WP_{ET} values at TL02, reflecting the small ranges in yield and LAI.

Total plant N and N use parameters

Total cumulative plant N at physiological maturity ranged from 46 to 91 kg ha^{-1} in 0-N plots and from 129 to 178 kg ha^{-1} in 180-N plots (Figure 5). Water regimes did not significantly affect total plant N within years. Total plant N at TL02 was lower than in the previous two years and further research has to clarify whether total plant N under conditions like those at TL02 is reduced by a lower crop N demand or by higher N losses or by a combination of both.

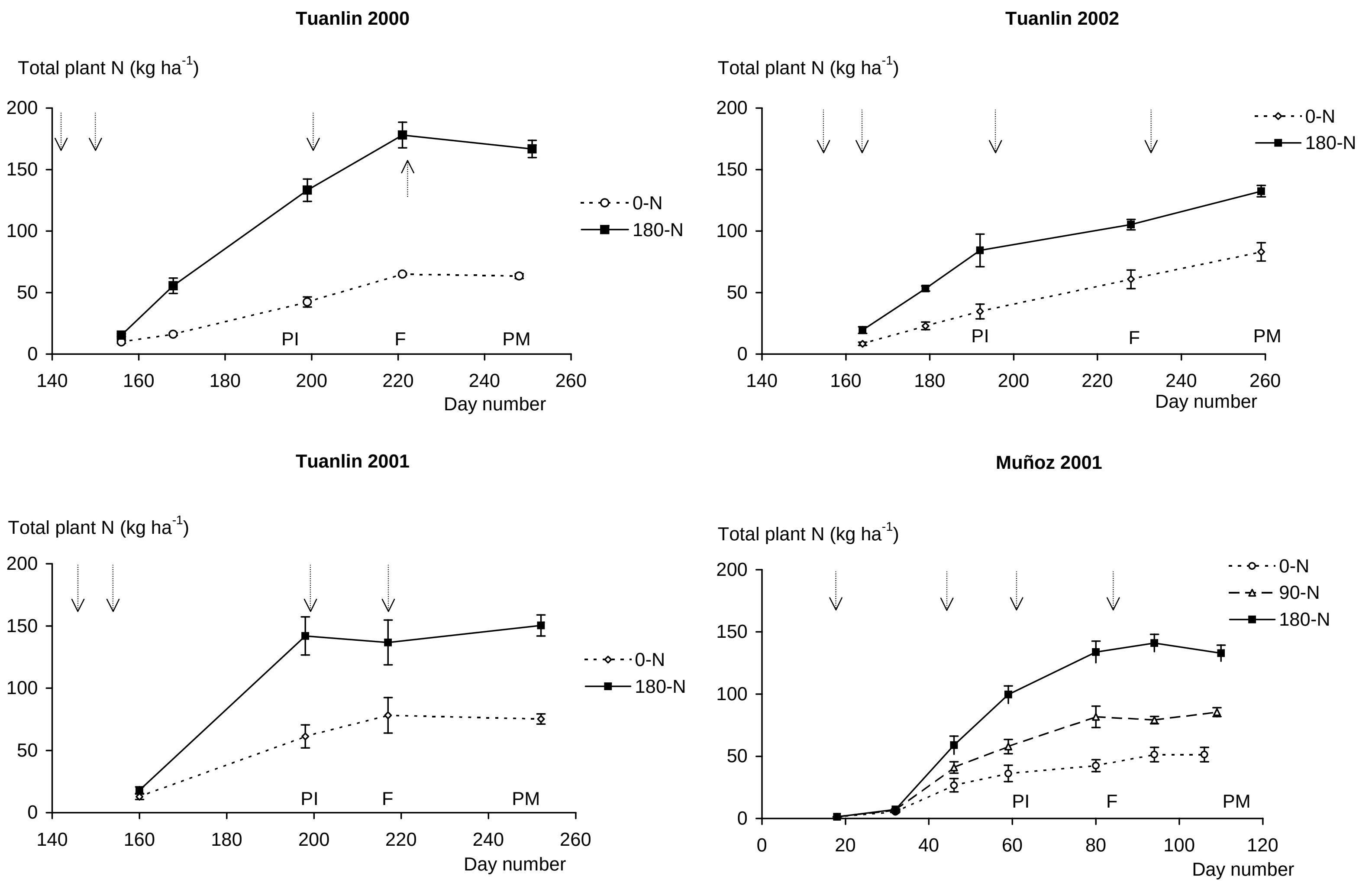

Figure 5. Total plant N during the rice cropping season at 0 and 180 kg N ha^{-1} at Tuanlin (China) and Muñoz (Philippines), 2000–2002 averaged over water regimes; arrows indicate fertilizer N applications; PI=panicle initiation, F=flowering, PM=physiological maturity.

N dilution as a function of total biomass with Greenwood type of curves indicated that crop N contents were below the critical N content for potential growing conditions as determined by Sheehy et al. (1998) for rice (Figure 6). The fitted *a* and *b* parameters for the N levels at Tualin and Muñoz are presented in Table 6. With the same biomass, plants without added N fertilizer had a lower N content than plants fertilized with 180 kg N ha^{-1}. The fitted N dilution curves could attribute at least 37% of the variation in plant N content to biomass in the control plots and at least 82% of the variation in plant N content to biomass at 180 kg N ha^{-1}. The *a* value, reflecting the N content when biomass is 1.0 t ha^{-1}, showed that when no fertilizer-N was applied the inbred cultivar had a higher initial N content (2.6%) than the hybrid cultivar (2.0%). The shape of the dilution curve, reflected by parameter *b*, indicated a retarded dilution in the hybrid compared with that in the inbred cultivar.

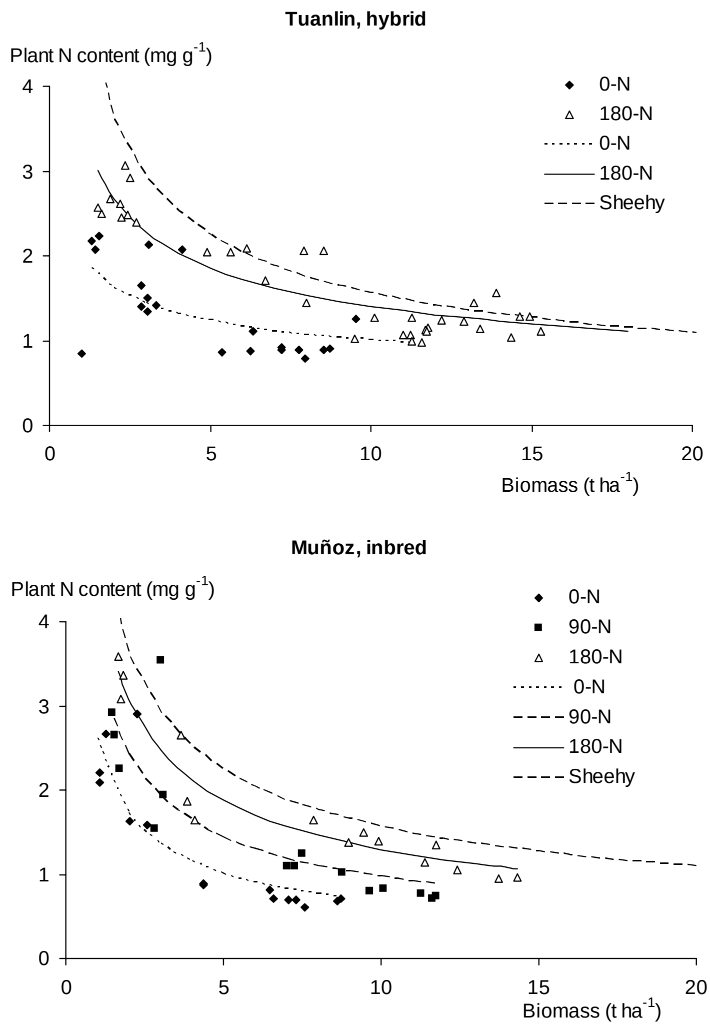

Figure 6. Nitrogen dilution curves of the inbred (at Muñoz) and hybrid (at Tuanlin) rice cultivars at 0, 90, and 180 kg N ha^{-1} and of critical N content in rice as determined by Sheehy et al. (1998).

Table 6. The *a* and *b* parameter values of the Greenwood N-dilution curve (see text for explanation).

Cultivar and location	N level	N	*a*	*b*	R^2
Hybrid, Tuanlin	0	21	2.00 ± 0.24	0.30 ± 0.09	0.37
	180	35	3.53 ± 0.19	0.40 ± 0.03	0.82
Inbred, Muñoz	0	15	2.62 ± 0.27	0.59 ± 0.11	0.74
	90	15	3.61 ± 0.47	0.57 ± 0.11	0.72
	180	15	4.49 ± 0.25	0.54 ± 0.04	0.94

Apparent N recovery (ANR) ranged from 0.21 to 0.72 (Table 4) and was significantly affected by water regime in two seasons (Table 5). For comparison, Cassman et al. (1993) reported that ANR in irrigated systems is typically 0.50 under good management. Also timing of N application significantly affected ANR at TL00. Highest values of ANR were obtained at TL00 with a relatively late dosing of N (17% basal, 20% 18 DAT, 27% 30 DAT, and 36% at PI) and lowest values were obtained at TL02. The higher ANR with more splits at TL00 was not related to the timing of submerged-nonsubmerged conditions but was the result of a better match between crop N demand and N supply.

At Tuanlin, ANR decreased with the number of days without ponded water (Figure 7a) and hence with increased aerobic soil conditions. The linear relationships between the number of nonsubmerged days until flowering and ANR (Figure 7a) and biomass yield (Figure 7b) show that both are affected by water availability. At Muñoz, ANR increased under SNS compared with continuously submerged conditions and showed the same response as biomass and grain yield.

Internal N use efficiency varied from 43 to 80 kg kg^{-1} (Table 4) and was significantly affected by N level but not by water treatments in all four experiments (Table 5). The lower internal N use efficiencies at high N application rates indicate that other factors (e.g., other nutrients, light) were limiting growth (Witt et al., 1999). Agronomic N use efficiencies ranged from 0 to 26 kg grain kg N $applied^{-1}$. Only at TL02 were agronomic N use efficiencies lower than 6 kg kg^{-1}, indicating that other factors than N application limited yields. Agronomic N use efficiency was significantly affected by water regime at TL01. In this season, also ANR and total aboveground biomass were significantly affected by water regime. The raised bed system consistently showed the lowest grain yield, biomass, and ANR at 180 kg N ha^{-1}. The other two water-saving regimes resulted in smaller yield and biomass reductions, while ANR was even higher than in SNS.

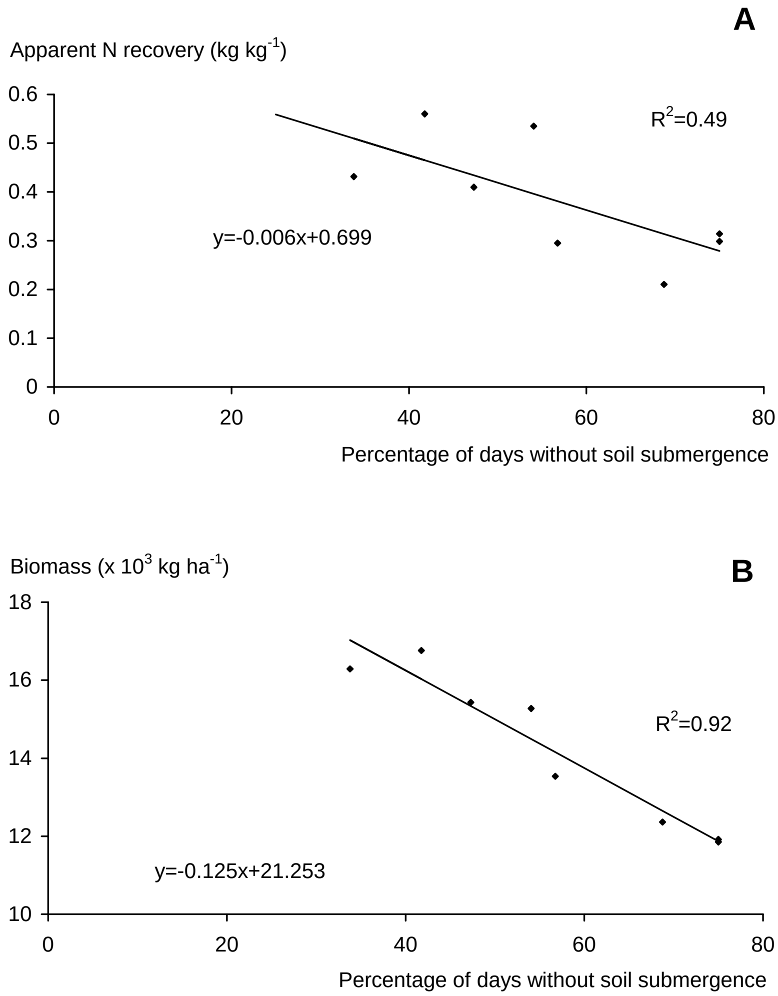

Figure 7. Apparent N recovery (A) and total above-ground biomass (B) versus the percentage of days without soil submergence between transplanting and flowering at Tuanlin (China) 2000–2002. For comparison, the apparent N recovery with full submergence was 0.55 kg kg^{-1}, while the total above-ground biomass was 16.8 t ha^{-1}. Dots are measured data and lines are regression curves.

Discussion

Water availability for irrigation has decreased in both the Zhanghe Irrigation System where Tuanlin is located (Loeve et al., 2004) and the area where Muñoz is located. In Zhanghe Irrigation System, the area of irrigated rice has declined and farmers started to adopt water-saving practices or switched to other crops (Hong et al., 2001). In central-Luzon, where Muñoz is located, irrigation supply is necessary to grow rice in the dry season, and water availability has been declining due to increasing urban demand (Hafeez, 2003). So the choice for location of the experiments was based on real and expected water shortages for irrigated lowland rice production.

Relatively small effects of water-saving regimes on grain yield within seasons occurred because of shallow groundwater tables (< 40 cm depth) in three seasons (TL00, TL01, and MU01), and because of water deficit in all treatments at TL02. The absence of a yield reduction under SNS in TL00 and MU01 was in line with Mao (1993), Li (2001), and Wu (1999). The groundwater level played an important role in the treatment effect of the irrigation regimes. Despite creating shallow barriers against seepage, continuously percolating water from surrounding flooded paddy fields made the groundwater table rise to shallow depths in the area of our experiments. Water-saving treatments thus led only to small differences in soil moisture status and the rice plants could easily extract water from the groundwater table. The TL02 season gives insight into a situation with a deeper groundwater table. In this season, all water-saving regimes led to water deficit, resulting in reduced grain yield and WP_{ET}. Although the frequency of irrigations remained the same throughout the season, there was no field submergence some 10 days after PI. Soil physical parameters that govern the vertical flow may have been changed during the season. Especially if cracks develop and penetrate through the hardpan, water permeability can increase tremendously (Bouman and Tuong, 2001). The deeper groundwater table as in TL02 might occur if all farmers decide to adopt water-saving technologies and water-saving technologies should be again evaluated after wide-scale adoption (see Chapter 5).

Crop water stress at soil water potentials of –30 to –50 kPa at TL02 was confirmed by Bouman and Tuong (2001), who found that grain yields were reduced when soil water potential was in the range between –10 to –40 kPa. Not only the groundwater table but also the percentage of days without submergence affected crop growth, total plant N, and grain yield (Figure 7), which also led to a significant effect of water regime on biomass and ANR (Table 5).

The conditions of our field experiments were representative for irrigated lowland rice environments in Asia. In poorly draining soils, small water savings can be made while maintaining high yields by reducing evaporation when the canopy is not yet closed. It may be concluded that in studies on water-saving strategies, groundwater table and soil water potential should be carefully monitored.

N management plays a key role in increasing yields per unit of land and per unit of water input and therefore in increasing WP_{ET}. Our findings show that a fast leaf development and a high rate of biomass increase are essential to achieve high grain yields. This may give support to the farmers' practice in China to apply most fertilizer-N early in the season (50% basal and 50% before 14 DAT). Hasegawa and Horie (1996) argued that the effect of N on LAI overrides the effect on photosynthesis, thus highlighting the strong relations among N availability, LAI, and biomass formation.

Yields in SNS with 180 kg N ha^{-1} at TL00 and TL01 were 0.8 and 1.9 t ha^{-1} higher than at Muñoz, respectively. This is partly explained by the 2−3 weeks' longer growing season at Tuanlin. Raised beds in this configuration in the heavy soil of Tuanlin seem not to be a promising water-saving technology. A different configuration may lead to better results. At TL02, grain yield in 0-N plots was on average 6.12 t ha^{-1} and only 9% lower than the plots fertilized with 180 kg N ha^{-1}. The preceding crop in the winter season of 2002 was highly fertilized wheat, while the fields in 2000 and 2001 had been fallowed during the winter before growing rice in the summer period. Residual N after wheat harvest was high what may have caused the relatively high rice yields in 0-N plots in 2002.

At Muñoz, ANR was significantly higher at 180 kg N ha^{-1} than at 90 kg N ha^{-1}. In general, the efficiency of an input decreases with an increased rate of application because other factors become limiting (de Wit, 1992). The lower ANR at Muñoz at 90-N may be caused by an early growth limitation due to N-stress.

Since sink size is determined at an early stage, it is necessary to study how N and water affect crop growth at an early stage. Our above analysis highlights the role of N for LAI and light interception. Wopereis et al. (1996a) showed that leaf expansion is the most sensitive physiological process to water deficit, thereby implying that water deficit in the vegetative phase may already limit the sink size.

To study the interaction of two major inputs for an agricultural system like rice production, one has to define suitable parameters to evaluate treatments and interactions. To evaluate water and N treatments on water use, we found WP_{ET} a useful parameter, since it enables the comparison between sites and cultivars. A water balance model would be useful to describe the exact flows of water in a field but is beyond the scope of this chapter. To describe N economy of these systems, we used a range of parameters of which total plant N and apparent N recovery are the most indicative. To evaluate crop N status using the N dilution concept of Greenwood et al. (1990) and the internal N use efficiency as defined by Witt et al. (1999), it is necessary to know that N dilution curves were validated for the time until flowering whereas internal N use efficiency was determined from plants at physiological maturity. A low value for internal N use efficiency as such, indicating maximum accumulation (Witt et al., 1999), doesn't automatically mean that potential yield was achieved. Maximum N accumulation indicates an imbalance in uptake of the nutrients N-P-K and moreover the internal N use efficiency is calculated at one point in time namely physiological maturity, whereas the Greenwood concept displays N dilution dynamically.

For optimizing N and water use, one has to define the main constraint to rice production. If it is water shortage, then increasing WP_{ET} should be the main goal. If water is amply available, then optimizing grain yields by improved N management should be the main goal. This chapter showed that variation in field hydrology, indigenous N supply, weather and cultivar choice all affect the crop growth. Therefore, a systems approach that covers all processes related to cultivar traits, N and water management can support the strategic and tactical decision process in sustainable rice production.

Acknowledgments

We thank ACIAR (Australian Center for International Agricultural Research), which funded the experiments at Tuanlin under ACIAR project LWR1/2000/030, and the staff of Tuanlin station and R. Cabangon of IRRI for their assistance in carrying out the experiments. We are also grateful to Dr. L. Sebastian, who provided us with the facilities and assistance to conduct the experiment at PhilRice. This research contributes to the Comprehensive Assessment of Water Management in Agriculture, supported by a grant from the Dutch Government of the Comprehensive Assessment of Water Management in Agriculture.

CHAPTER 4

Crop performance, nitrogen and water use in flooded and aerobic rice [1]

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Abstract

Irrigated 'aerobic rice' is a new system being developed for lowland areas with water shortage and for favourable upland areas with access to supplementary irrigation. It entails the cultivation of nutrient-responsive cultivars in non-saturated soil with sufficient external inputs to reach yields of 70–80% of high-input flooded rice. To obtain insights into crop performance, water use, and N use of aerobic rice, a field experiment was conducted in the dry seasons of 2002 and 2003 in the Philippines.

Cultivar Apo was grown under flooded and aerobic conditions at 0 and at 150 kg fertilizer N ha^{-1}. The aerobic fields were flush irrigated when the soil water potential at 15-cm depth reached –30 kPa. A ^{15}N isotope study was carried out in microplots within the 150-N plots to determine the fate of applied N.

The yield under aerobic conditions with 150 kg N ha^{-1} was 6.3 t ha^{-1} in 2002 and 4.2 t ha^{-1} in 2003, and the irrigation water input was 778 mm in 2002 and 826 mm in 2003. Compared with flooded conditions, the yield was 15% and 39 % lower, and the irrigation water use 36% and 41% lower in aerobic plots in 2002 and 2003, respectively. N content at 150 kg N ha^{-1} in leaves and total plant was nearly the same for aerobic and flooded conditions, indicating that crop growth under aerobic conditions was limited by water deficit and not by N deficit. Under aerobic conditions, average fertilizer N recovery was 22% in both the main field and the microplot, whereas under flooded conditions, it was 49% in the main field and 36% in the microplot. Under both flooded and aerobic conditions, the fraction of ^{15}N that was determined in the soil after the growing season was 23%. Since nitrate contents in leachate water were negligible, we hypothesized that the N unaccounted for were gaseous losses. The N unaccounted for was higher under aerobic conditions than under flooded conditions. For aerobic rice, trials are suggested for optimizing dose and timing of N fertilizer. Also further improvements in water regime should be made to reduce crop water stress.

Keywords: Aerobic rice, nitrogen, apparent nitrogen recovery, water savings, N losses, ^{15}N balance.

[1] Plant and Soil (2005) in press.

Introduction

Asia's food security depends largely on irrigated lowland rice fields, which produce three-quarters of all rice harvested (Maclean et al., 2002). However, the increasing scarcity of fresh water threatens the sustainability of the irrigated rice ecosystem (Guerra et al., 1998; Tuong and Bouman, 2003). Irrigated lowland rice in Asia usually has standing water for most of the growing season. Field techniques to actively save irrigation water were explored over the years and include direct (dry) seeding, keeping fields at soil saturation, and keeping fields alternately submerged-nonsubmerged. In an overview of these techniques, Bouman and Tuong (2001) concluded that, compared with flooded rice, small yield reductions of 0–6% occurred under saturated conditions, and larger yield reductions of 10–40% occurred under alternate submergence-nonsubmergence, when soil water potentials during the nonsubmerged phase reached values between –10 and –40 kPa.

A new development in water-saving technologies is the concept of "aerobic" rice (Bouman, 2001; Bouman et al., 2005). In aerobic rice systems, fields remain unsaturated throughout the season. Rice has been grown under nonflooded, aerobic soil conditions in uplands for centuries, but yields are on average only 1–2 t ha^{-1} because of adverse environmental conditions (poor soils, little rainfall, weeds), low use of external inputs, and low yield potential of upland rice cultivars (Khush, 1997). The new concept of aerobic rice entails the use of nutrient-responsive cultivars that are adapted to aerobic soils (Bouman, 2001; Lafitte et al., 2002), aiming at yields of 70-80% of high-input flooded rice. The target environments are irrigated lowlands with water shortage and favourable uplands with access to supplementary irrigation. Irrigation can be by surface irrigation (e.g., flush irrigation, furrow irrigation) or by sprinklers, and aims at keeping the soil 'wet' but not flooded or saturated. In practice, irrigation will be applied to bring the soil water content up to field capacity once a lower threshold has been reached. For upland crops such as wheat or maize, this threshold is usually the soil water content halfway between field capacity and wilting point (Doorenbos and Pruit, 1984), but, for aerobic rice, the optimum threshold for re-irrigation still needs to be determined.

In Asia, special aerobic, nutrient-responsive rice cultivars have been developed already in northern China with a temperate climate (Wang et al., 2002) and research is under way to establish crop-water response functions (Yang et al., 2002). In tropical Asia, the International Rice Research Institute (IRRI) recently identified some existing improved upland and lowland cultivars that do well under aerobic conditions (George et al., 2002; Lafitte et al., 2002), but a quantification of water use and yield under well-documented aerobic conditions is still lacking.

Since the concept of aerobic rice is new, relatively few insights exist into nitrogen

(N) dynamics and fertilizer N use. In flooded rice with saturated anaerobe soils, ammonium is the dominant form of available N. Most of the losses of fertilizer N occur immediately after application into the floodwater through ammonia volatilization (Vlek and Craswell, 1981). Some of the ammonia is nitrified in oxidized soil zones and in the floodwater (De Datta, 1981). This nitrate (NO_3) moves into reduced layers, where it denitrifies and is subsequently lost to the atmosphere as N_2 and N_2O (De Datta, 1981). Since NO_3 is barely present in flooded rice soils, very little NO_3-N is leached to the groundwater (Bouman et al., 2002). In aerobic systems, on the other hand, the dominant form of N is NO_3 and relatively little ammonia volatilization can be expected after fertilizer-N application. The application of irrigation water will create soil moisture conditions close to saturation immediately following irrigation and below field capacity a few days later. These alternate moist-dry soil conditions may stimulate nitrification-denitrification processes (Reddy and Patrick, 1976; Eriksen et al., 1985), resulting in a loss of nitrogen through N_2 and N_2O. In addition, nitrate is prone to leaching. The differences in soil N dynamics and pathway of N losses between flooded and aerobic systems may result in different fertilizer-N recoveries.

Cassman et al. (2002) compared the apparent N recovery of maize grown in the USA and flooded rice in Asia and found on average a higher value for maize (0.37±0.30) than for flooded rice (0.31±0.18). Although obtained in different climatic regions with different crops, this suggests that upland systems can have equal or higher values of N recovery than flooded systems. However, field experiments are needed to compare fertilizer-N uptake and recovery between flooded and aerobic rice systems.

Recently, a study began at IRRI to compare crop growth, yield, water use, and N use of rice under flooded and aerobic conditions in the tropics. In this chapter, we report on the crop performance and N use under flooded and aerobic conditions in two seasons using a nutrient-responsive upland cultivar. The analysis includes a comparison of the fate of fertilizer N in the two rice ecosystems.

Materials and methods

Treatments and design

The study was done in the dry seasons (January–May) of 2002 and 2003, and was embedded in a long-term experiment comparing rice under flooded and aerobic conditions since 2001 at IRRI, Los Baños, the Philippines (14°18′ N, 121°25′ E) (Bouman et al., 2005). The choice for the dry season was based on the local rainfall pattern. In the years 1979–2003, the rainfall from January to May was 290±31 mm while rainfall in the wet season from June until October was 1333±55 mm. Since in the wet season, true aerobic conditions were hard to impose, we decided to use only the dry season in our study. The soil of the experiment was a typic Tropaqualf, with 59% clay, 32% silt, and 9% sand, a total C content of 19.8 g kg^{-1}, and pH of 6.7.

Flooded fields always had standing water from transplanting until about 1 week before physiological maturity, with water depths increasing from 2 cm at transplanting to 10 cm at panicle initiation. Aerobic fields were kept saturated the first week after transplanting and then re-irrigated when the soil water potential at 15 cm depth reached −30 kPa. This threshold for soil water potential was based on results from research in alternately submerged-nonsubmerged systems (O'Toole and Baldia 1982; Wopereis et al., 1996a; Bouman and Tuong, 2001; Belder et al., 2004). Around flowering, the threshold for irrigation was reduced to −10 kPa (field capacity) to avoid spikelet sterility (O'Toole and Garrity, 1984). Irrigations in 2002 were based on average soil water potential values over all four replicates, whereas in 2003, irrigations were based on soil water potential values of individual main plots. This change was based on observed heterogeneity between the replicates. Land preparation in the flooded fields consisted of wet tillage and harrowing (puddling), whereas in aerobic fields, dry tillage and harrowing were practiced. Drains of 0.4 m deep surrounded each field and plastic sheets were installed to 0.4 m depth in the bunds to separate the fields hydrologically. Flooded and aerobic fields were divided into one subplot receiving no fertilizer-N (0-N plot) and another subplot receiving 150 kg urea-N ha^{-1} (150-N plot) in three splits: 50 kg N ha^{-1} basal, 50 kg N ha^{-1} at 25 days after transplanting (DAT), and 50 kg N ha^{-1} at 45 DAT. Subplot size was 86 m^2 and all treatments were replicated four times. P, K, and Zn fertilizers were incorporated in each subplot one day before transplanting at a rate of 60, 40, and 5 kg ha^{-1}, respectively. Seedlings were transplanted at a spacing of 10 × 25 cm, with two seedlings per hill. Seedling age at transplanting was 20 days in 2002 and 24 days in 2003, and transplanting dates were 24 January in 2002 and 4 February in 2003. The cultivar that was used during both seasons was the improved upland cultivar Apo (IR55423-01). The choice for this cultivar was based on good performance under aerobic conditions and the responsiveness to nutrients (George et al., 2001). In the long term experiment, several other cultivars were tested (Bouman et al., 2005).

Intensive pest and weed management was applied using a combination of pesticides, herbicides, and manual weed control. Weed pressure was much higher in aerobic than in flooded plots and weeds were manually removed several times before the canopy of the rice crop was closed.

Microplots of 0.8 × 1.0 m containing 32 hills were established in the flooded and aerobic 150-N plots. Each microplot was surrounded by metal plates that were 30 cm high and were inserted 15 cm deep in the soil before the basal fertilizer application. The microplot study was designed as a split plot with water regime as the main factor and N timing as the sub factor. The two water regimes were aerobic and flooded. N timing followed the splits in the 150-N plots so that ^{15}N labelled urea was applied either basal, 25 DAT, or 45 DAT. Unlabelled 'normal' urea was applied at the other two splits. The application method followed that in the main plot. Weak seedlings were replaced within the first 2 weeks after transplanting. Microplots had the same water regime as the main plots, but received irrigation water separately using buckets to avoid exchange of N. Any weeds were uprooted and put on top of the soil.

In between the two dry seasons of our experiments, both the flooded and aerobic fields were cropped with flooded rice (cultivar Apo) in the wet seasons (June-October). The 0-N plots again received 0 kg N ha^{-1} and the 150-N plots received 70 kg N ha^{-1}.

Measurements and calculations

Weather data were collected from a weather station at the site, and included daily rainfall, air temperature, and radiation. Seasonal means and sums are reported for the treatment with the longest growth duration. Growth duration was measured from transplanting until physiological maturity. Vapour pressure deficit was calculated as the difference between the saturated vapour pressure of the average daily air temperature and the early morning vapour pressure.

Irrigation water was supplied to each field through 6-inch PVC pipes that spilled water into 90° boxed-weirs (V-notch type). The amount of water applied was monitored at each irrigation by measuring the depth of water over the V-notch. The groundwater table depth was measured daily in fully perforated PVC pipes installed down to 1.75 m in bunds separating subplots. Tensiometers were installed at 15 and 35 cm depth in the aerobic fields for daily measurement of the soil water potential. Water-filled pore space was computed from the soil water potential values and the soil water retention characteristics, which were determined from undisturbed soil samples taken from the same site.

In 2002, NO_3 concentrations were measured from soil water samples collected at 30 and 60 cm depth in 150-N aerobic plots, and from samples collected in the groundwater tubes in aerobic and flooded 150-N plots. In 2003, NO_3 concentration was determined from soil solution at 60 and 150 cm depth in both aerobic (0-N and 150-N) and flooded plots (0-N and 150-N). Water samples were stored at 4 °C and filtrated before analysis. Nitrate was determined colourimetrically, using the Technicon autoanalyzer method (Technicon Bulletin, 1986).

Crop samples were taken seven times in 2002 and eight times in 2003 at regular intervals of 10−15 days to determine above-ground biomass, leaf area index (LAI), and total plant N during the season. At each sampling, two areas of 0.25 m^2, comprising 10 hills each, were harvested from opposite sides in the plot. Plants were divided into green leaf blade, stem plus leaf sheath, dead leaf (if any), and panicle (if any). LAI was measured using a Licor LI3100 area meter. Biomass was determined after drying the samples at 70 °C for three days. Tissue N content was determined using the Kjeldahl method (Bergersen, 1980) and is reported for green leaf as 'leaf-N content' and for total above-ground plant material as 'total plant-N content'. Grain yield was determined at maturity as the mean of two 5-m^2 samples per plot and is reported at 14% moisture content.

Water productivity was calculated as kg grain m^{-3} total water input (rainfall and the sum of all irrigations, including land preparation), WP_{I+R}. Apparent N recovery (ANR) was calculated with the difference method using the total plant N at physiological maturity

$$\mathrm{ANR} = \frac{N_{\mathrm{tot,f}} - N_{\mathrm{tot,uf}}}{N_{\mathrm{applied}}} \qquad (\mathrm{kg\ kg^{-1}}) \qquad (1)$$

where $N_{tot,f}$ and $N_{tot,uf}$ are total amounts of plant N in fertilized and unfertilized plots (kg ha^{-1}), respectively, and $N_{applied}$ is the amount of fertilizer-N applied (kg ha^{-1}).

In the microplots, all plants were cut at ground level at maturity and oven dried at 70 °C for 3 days. Plants of the four central hills were separated into grain and straw. Immediately after the plants were harvested, two soil samples per microplot were taken, comprising two of the four central hills. Each sample covered a surface area of 10 × 25 cm, was 30 cm deep, and included the roots of the plants. The soil samples were sectioned into three layers: 0−5 cm, 5−15 cm, and 15−30 cm. Roots were separated from the soil and rinsed with de-ionized water before oven drying. Water content of each soil layer was determined by drying other subsamples for 48 hours at 105 °C. Other soil subsamples from each soil layer were dried at 40 °C for 3 weeks prior to N and ^{15}N analysis. All plant and soil samples were fine-ground to <0.15 mm prior to N content analyses. N-total and atom% ^{15}N analyses were done with an automated C-N analyzer-mass spectrometer (ANCA-MS) similar to that described by Bronson et al. (2000).

Analysis of variance was based on a split-plot design with water as the main factor and N level as the sub factor. In the microplot study, water was the main factor and ^{15}N timing was the sub factor. Pair-wise comparisons between the aerobic and flooded treatment at 0-N and 150-N were carried out for the crop parameters grain yield, total plant N, and N content of leaves and total plant. Pair-wise comparisons between the aerobic and flooded treatment at 150-N were carried out for apparent N recovery and for N contents in the three soil layers.

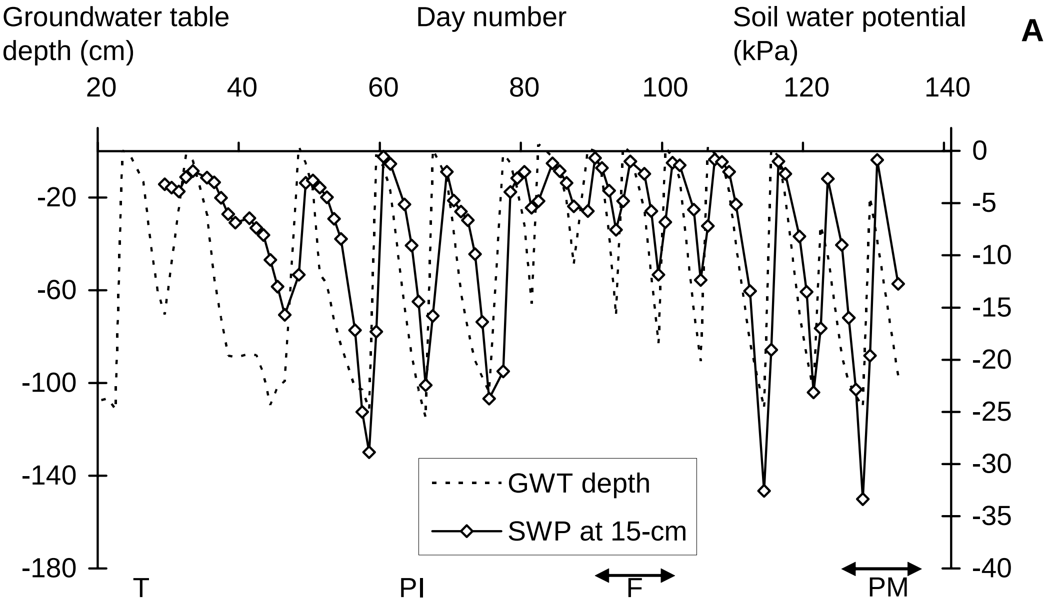
Results

Weather
Average air temperature from transplanting to harvest was 26.9 ± 1.6 °C in 2002 and 27.5 ± 1.7 °C in 2003. Radiation sums were almost identical, with 2352 MJ m^{-2} $season^{-1}$ in 2002 and 2359 MJ m^{-2} $season^{-1}$ in 2003, and seasonal rainfall was 58 mm in 2002 and 92 mm in 2003. Average daily vapour pressure deficit was identical in the two years at 0.80±0.17 kPa.

Main plots

Water Total irrigation water input in flooded plots, including that for land preparation, was 1214 mm in 2002 and 1398 mm in 2003. Total irrigation water input in aerobic plots was 778 mm in 2002 and 826 mm in 2003, resulting in water savings of 436 and 572 mm $season^{-1}$ compared with flooded plots. The irrigation water inputs for flooded plots were comparable with those observed in heavy soils by Tabbal et al. (2002), and Bouman and Tuong (2001). Groundwater table depth and soil water potential at 15 cm depth in aerobic plots in 2002 and 2003 are given in Figure 1. Consecutive irrigations caused the groundwater table to rise to the soil surface, and, subsequently, values of soil water potential came close to 0 kPa. The seasonal-average soil water potential in aerobic plots at 15 cm depth was −10 kPa (± 8 kPa) in 2002 and −7 kPa (± 9 kPa) kPa in 2003. The average soil water potential at 35 cm depth was −5 kPa (±3 kPa) in 2002 and −9 kPa (±7 kPa) in 2003. Groundwater table depth in flooded plots was mostly within 30 cm of the soil surface until about one week before physiological maturity. Shallow groundwater tables of < 30 cm depth under flooded rice fields were also observed by Belder et al. (2004). The frequency distribution of the daily water-filled pore space in aerobic plots at 15 cm depth is given in Figure 2. In both 2002 and 2003, the soil was close to saturation most of the time, with a minimum water-filled pore space of 82% in 2002.

Nitrate in groundwater and soil solution Nitrate concentrations in groundwater tubes (2002) and at 150 cm depth (2003) were below 2 mg l^{-1} in both flooded and aerobic plots (Figure 3). These low values indicate very low leaching losses in both flooded and aerobic fields. Maximum nitrate concentrations in soil solution (30 and 60 cm depth, in 2002) in aerobic plots reached values of 7.5 mg l^{-1} and reflected temporal patterns of fertilizer-N applications. Sampling the soil solution in 2003 at 60 and 150 cm showed no differences in nitrate concentrations between flooded and aerobic plots, between 0-N and 150-N plots, and between the two sampling depths (Figure 3 C−D).



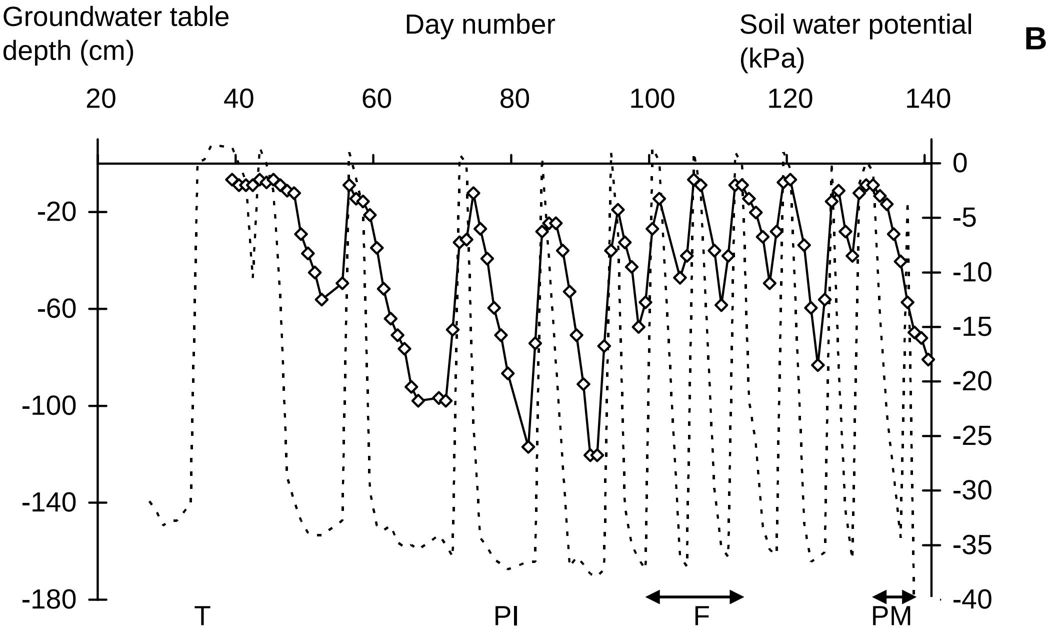


Figure 1. Groundwater table (GWT) depth (------) and soil water potential (SWP) at 15-cm depth (—◊—) in aerobic plots in (A) 2002 and (B) 2003; in 2002 the lines represent averages over four replicates and in 2003 the lines represent only one replicate. T=transplanting, PI=panicle initiation, F=flowering, PM=physiological maturity.

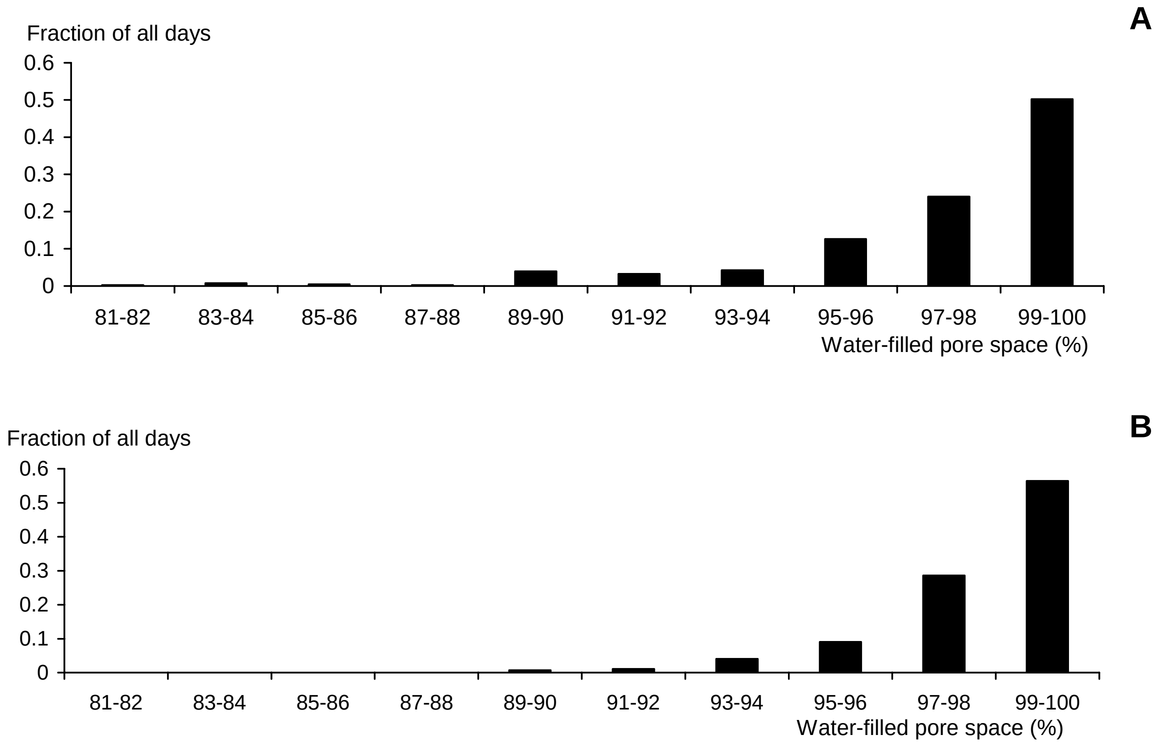


Figure 2. Frequency distribution of water-filled pore space in aerobic plots at 15-cm depth in (A) 2002 and (B) 2003.

Crop growth and development, yield, and water productivity In the 150-N plots, the temporal curves of LAI, biomass, and total plant N were all lower under aerobic conditions than under flooded conditions in both years (Figure 4). Maximum LAI in flooded plots was 6.3–6.5, while maximum LAI in aerobic plots was 4.6 in 2002 and 3.3 in 2003. The low LAI values in aerobic plots in 2003 were associated with reduced total biomass and grain yield at the end of the growing season (Table 1). With 150 kg N ha^{-1}, the yield under aerobic conditions was 15% lower than under flooded conditions in 2002, and 39% lower than under flooded conditions in 2003. In a pair-wise comparison, these differences were statistically significant at $P<0.03$ in 2002 and $P<0.001$ in 2003. Many plants in flooded 150-N plots lodged shortly before maturity. In the 0-N plots, the temporal curves of LAI, biomass, and total plant N were comparable between the aerobic and the flooded plots. The yield in aerobic 0-N plots was only 9–13% lower than in flooded plots, and the differences were not significant ($P<0.05$).

The factors water and N both affected crop growth duration (Table 1). Crop duration was shortest in the flooded plots with 150-N in both years. In 2002, the aerobic 150-N plots matured 8 days earlier than the 0-N plots under both flooded and aerobic conditions, while in 2003 there was no difference.

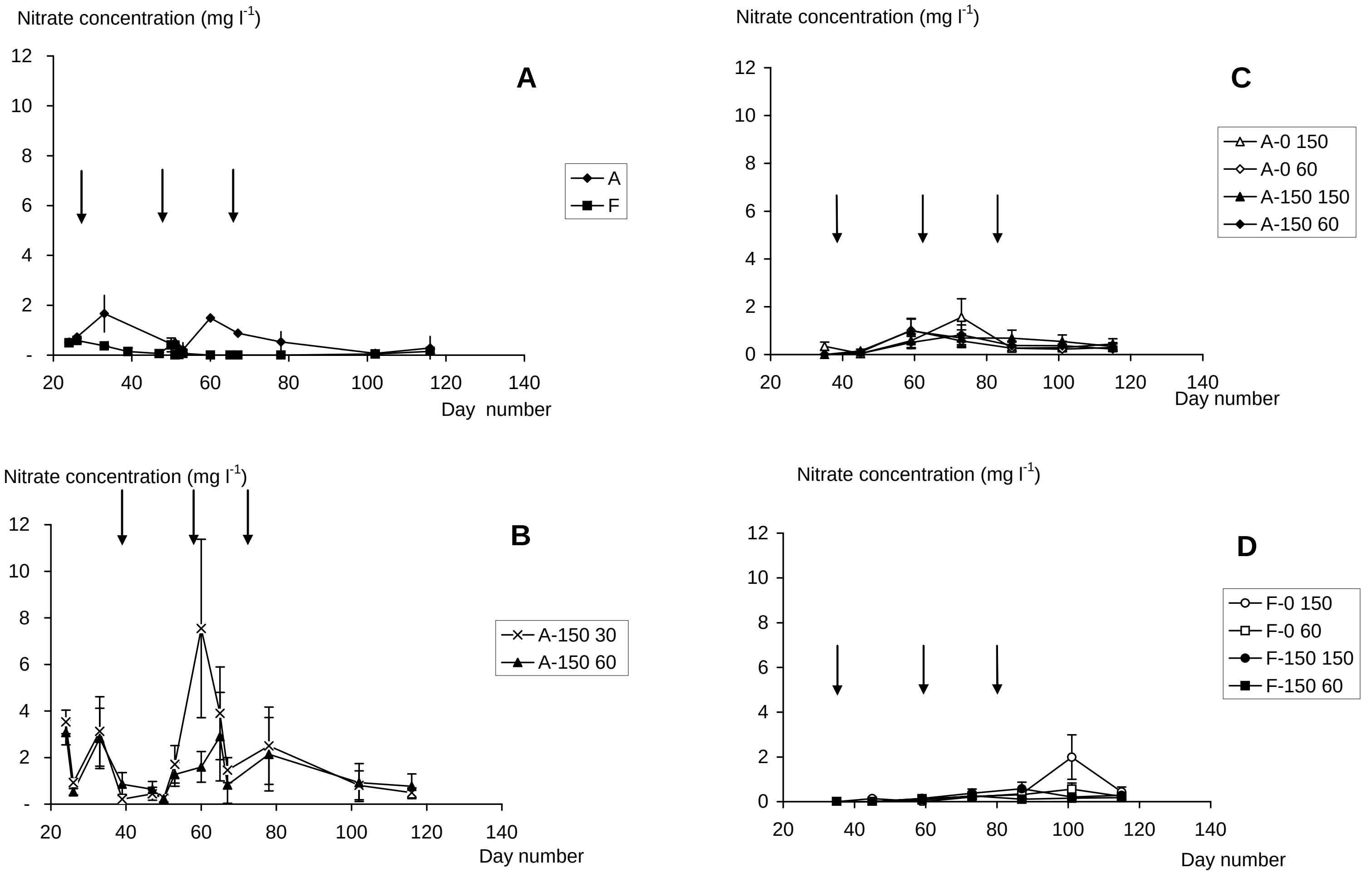


Figure 3. Nitrate concentrations in (A) 2002 in groundwater in aerobic, (A, ♦) and flooded (F, ■) plots; (B) 2002 in soil solution at 30-cm (A 30, ×) and 60-cm (A 60, ▲) in aerobic plots; (C) 2003 in 0-N aerobic plots at 60-cm (A-0 60, ◊) and 150-cm (A-0 150, Δ) depth and in 150-N plots at 60-cm (A-150 60, ♦) and at 150-cm (A-150 150, ▲); (D) 2003 in flooded 0-N plots at 60-cm (F-0 60, □) and at 150-cm (F-0 150, ○) depth and in 150-N plots at 60-cm (F-150 60, ■) and at 150-cm (F-150 150, ●). Bars indicate the standard error; arrows indicate fertilizer-N applications.

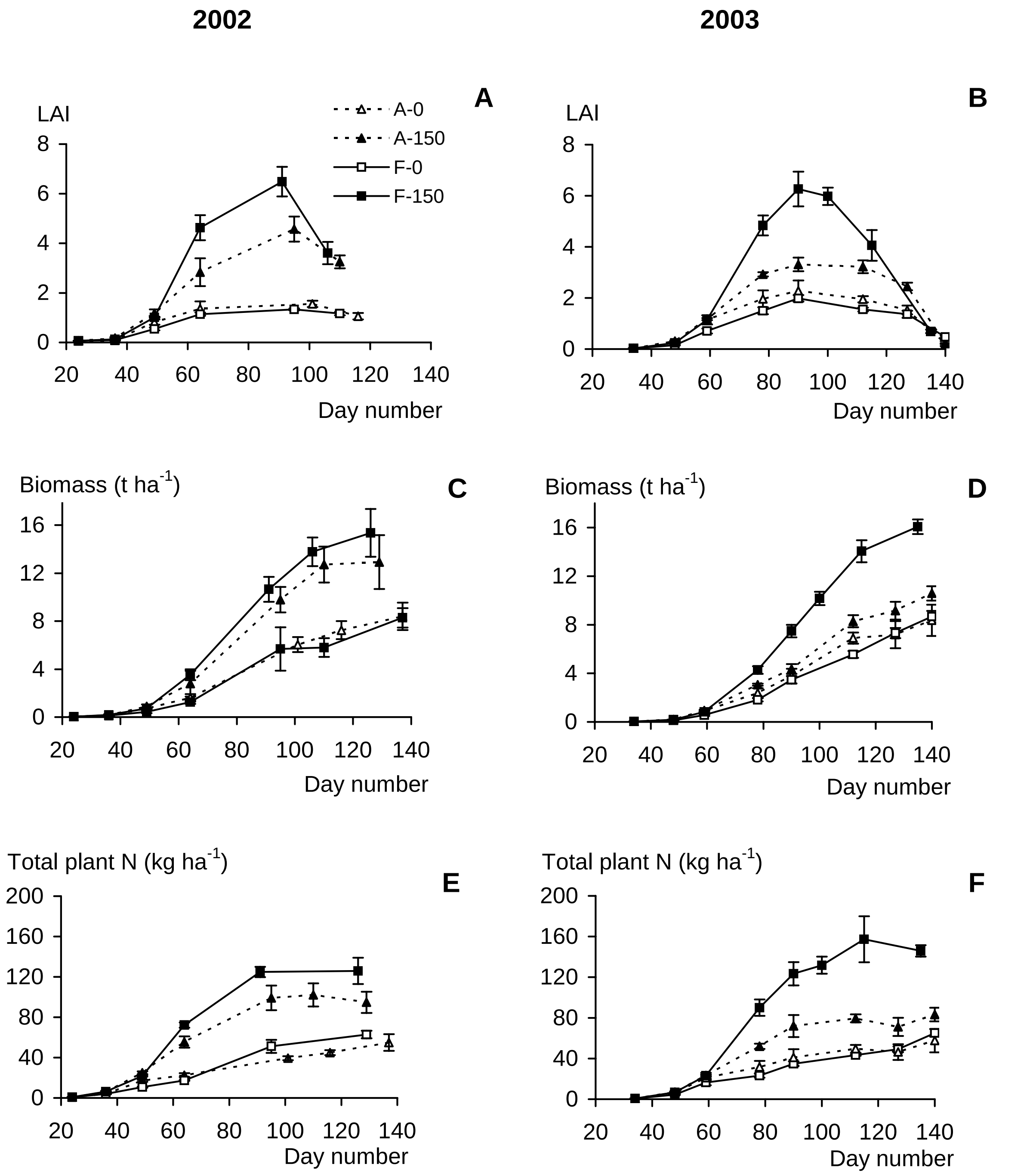


Figure 4. LAI in time in (A) 2002 and (B) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, Δ) and with 150-N (A-150, ▲); above-ground biomass in time in (C) 2002 and (D) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, Δ) and with 150-N (A-150, ▲); and total plant N in time in (E) 2002 and (F) 2003, under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, Δ) and with 150-N (A-150, ▲). Bars indicate the standard error.

Table 1. Biomass (t ha^{-1}), total plant N (kg ha^{-1}), grain yield (t ha^{-1}), water productivity (kg m^{-3}), and crop duration (days) of Apo at maturity in 2002 and 2003 with analysis of variance.

Year	Treatment	Biomass	Total plant N	Grain yield	Water productivity	Crop duration[b]
2002	flooded 0-N	8.6	66	3.8	0.31	113
	flooded 150-N	16.0	133	7.3	0.59	102
	aerobic 0-N	8.7	58	3.3	0.40	113
	aerobic 150-N	13.4	98	6.3	0.75	105
2003	flooded 0-N	8.7	65	4.1	0.28	106
	flooded 150-N	16.1	146	6.8	0.47	101
	aerobic 0-N	8.4	58	3.7	0.40	106
	aerobic 150-N	10.6	83	4.2	0.45	106
Analysis of variance						
2002	water	ns[a]	ns	ns	ns	
	N level	***[a]	**	***	***	
	water × N level	ns	ns	ns	ns	
	coefficient of variance	16.0	21.7	8.5	10.5	
2003	water	ns	ns	*	ns	
	N level	***	***	**	**	
	water × N level	**	**	**	*	
	coefficient of variance	12.4	11.3	12.8	14.2	

[a] ns = nonsignificant (P>0.05); * P<0.05, ** P<0.01, *** P<0.001

[b] Maturity per treatment was determined in the field as average over four replicates and, therefore no statistics were calculated.

Yield components are presented in Table 2. Sink size, represented by the number of grains per m^2, showed a strong response to N and reflected LAI and biomass growth. Grain filling was significantly (P<0.05) affected by water regime in both seasons and was below 77% in aerobic plots. In comparison, around 90% of the grains were filled in 0-N flooded plots. Individual grain weight showed a slight but significant effect of N (P<0.001) in 2002 and water regime (P<0.01) in 2003. All three components of yield were lower for aerobic than flooded conditions so that there was no positive feed-back mechanism between yield components. This finding means that water deficit under aerobic cultivation lasted from around panicle initiation until physiological maturity, and even lowering the threshold of re-irrigation to –10 kPa around flowering still led to reduced grain filling. Flowering in 2003 occurred shorter after the soil water potential reached –30 kPa than in 2002 (Figure 1). This stress might have caused the

Table 2. Yield components of the cultivar Apo in the dry seasons of 2002 and 2003 under aerobic and flooded conditions.

Year	Treatment	Grain number (nr m^{-2})	Filled grains (%)	Individual grain weight (mg)
2002	flooded 0-N	21858	90.1	20.9
	flooded 150-N	39285	82.1	21.4
	aerobic 0-N	23367	76.7	19.9
	aerobic 150-N	33660	74.7	20.7
2003	flooded 0-N	21891	89.6	20.0
	flooded 150-N	43573	80.4	20.6
	aerobic 0-N	24218	74.4	18.2
	aerobic 150-N	31751	72.6	18.6
Analysis of variance				
2002	water	ns[a]	*[a]	ns
	N level	***	ns	***
	water × N level	ns	ns	ns
	coefficient of variance	14.1	5.8	1.1
2003	water	ns	*	**
	N level	***	*	ns
	water × N level	ns	ns	ns
	coefficient of variance	13.1	4.2	2.2

[a] ns = nonsignificant (P>0.05); * P<0.05, ** P<0.01, *** P<0.001.

lower growth rate between panicle initiation and flowering and the reduction in percentage grain filling and individual grain weight as compared with 2002 (Table 2).

Water productivity (WP_{I+R}) was increased by application of 150 kg N ha^{-1} in both flooded and aerobic plots and was highest for aerobic 150-N plots in 2002: 0.75 kg m^{-3} (Table 1). In 2003, WP_{I+R} in all treatments was lower than in 2002 and the effect of N on WP_{I+R} was smaller in both flooded and aerobic plots.

N content, uptake, and recovery The dynamics of N content in leaves and total plant are presented in Figure 5. Differences in N content of both leaves and total plant were significant in 2002 and 2003 between 0-N and 150-N plots. In 2002, the leaf-N content did not differ significantly between aerobic and flooded plots for most sampling dates at both N levels. Only in 2003, the leaf N content in 150-N plots was significantly lower under aerobic conditions than under flooded conditions at two sampling dates in the vegetative phase. The same trends were observed in N content of the total plant.

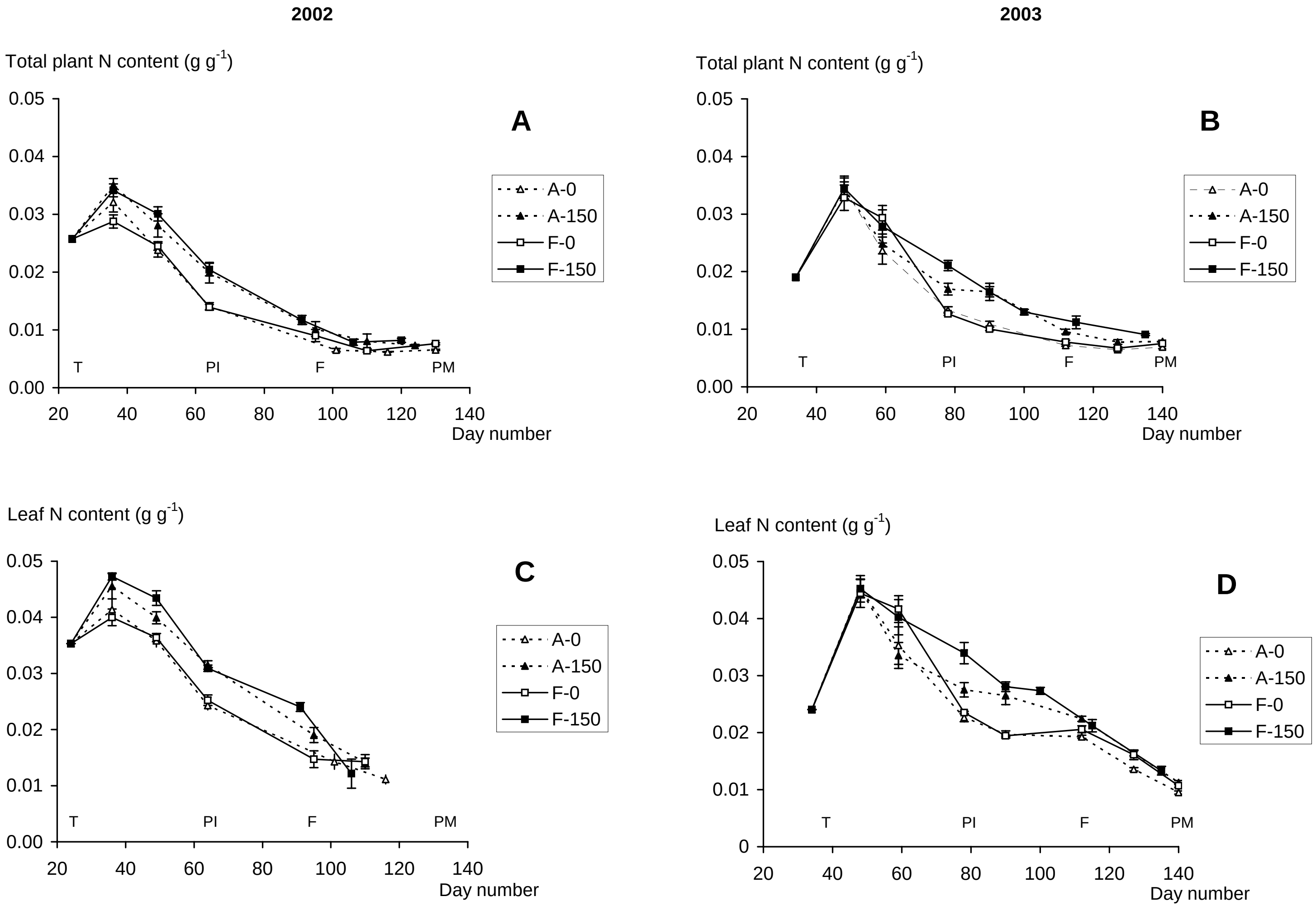


Figure 5. Plant-N content in time in (A) 2002 and (B) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, Δ) and with 150-N (A-150, ▲); and leaf-N content in time in (C) 2002 and (D) 2003 under flooded conditions with 0-N (F-0, □) and with 150-N (F-150, ■), and under aerobic conditions with 0-N (A-0, Δ) and with 150-N (A-150, ▲). Bars indicate the standard error. T=transplanting, PI=panicle initiation, F=flowering, PM=physiological maturity.

Table 3. Mean apparent N recoveries (kg kg^{-1}) with standard error in aerobic and flooded plots in 2002 and 2003.

Year	Aerobic	Flooded
2002	0.27 ± 0.08	0.44 ± 0.10
2003	0.17 ± 0.04	0.54 ± 0.05

Total plant N in the 150-N plots was on average 89 kg ha^{-1} under aerobic conditions, which was only 65% of the total plant N under flooded conditions (Table 1). In the 0-N plots, total plant N was on average 62 kg ha^{-1} and barely differed between year and water regime. The apparent N recovery was in both seasons significantly lower in aerobic plots (average 0.22 kg kg^{-1}) than in flooded plots (average 0.49 kg kg^{-1}, Table 3).

Microplots

The recovery of ^{15}N in grain and straw was higher under flooded than under aerobic conditions, in both 2002 (P<0.102) and 2003 (P<0.003) (Tables 4−5). Averaged over the different timings, plant-N recovery was 0.22 kg kg^{-1} in aerobic plots and 0.36 kg kg^{-1} in flooded plots. Timing of fertilizer-N application also influenced plant ^{15}N recovery, but only significantly so in 2003. The amount of ^{15}N recovered increased with later N application. Plant ^{15}N recoveries were lower in aerobic plots than in flooded plots at all timings of urea-N application. ^{15}N recovered by roots was not significantly affected by water regime or timing of N application, and was a fairly constant fraction of 0.03 of total applied ^{15}N.

The lower N recovery under aerobic conditions than under flooded conditions is corroborated by a ^{15}N isotope study by De Datta et al. (1983) in submerged-nonsubmerged regime (SNS) and continuously flooded water regimes. They reported a recovery of 0.41 under continuously flooded conditions and 0.20 under SNS conditions.

The fraction of ^{15}N measured in the top 30 cm of the soil in 2002 was higher under flooded conditions (0.33) than under aerobic (0.24) conditions. In 2003, however, the ^{15}N recovered from the soil was higher in aerobic (0.31) plots than in flooded (0.22) plots. For all applications, more than 50% of ^{15}N found in the soil was found in the top 5 cm (Tables 6−7). Relatively more ^{15}N was measured in the top 5 cm in flooded plots than in aerobic plots, indicating that fertilizer N moved deeper in the aerobic soil than in the flooded soil. Of the total soil N in the top 30 cm, 21% was present in the top 5 cm (Table 8), indicating that relatively more native N stayed in the two deeper layers than the fertilizer N applied during the experiment. This can be explained by the fact that, except for the basal-N application, the fertilizer N was not mixed with the soil.

Table 4. Recovery fraction of ^{15}N-enriched fertilizer N in microplots in 2002 with analysis of variance.

Treatment	Grain	Straw	Roots	Soil	Unaccounted for
aerobic					
basal	0.13	0.10	0.02	0.21	0.55
25 DAT[a]	0.14	0.13	0.04	0.24	0.45
45 DAT	0.17	0.14	0.03	0.26	0.40
average	0.14	0.12	0.03	0.24	0.47
flooded					
basal	0.23	0.10	0.04	0.44	0.20
25 DAT	0.21	0.09	0.02	0.25	0.43
45 DAT	0.32	0.14	0.02	0.29	0.23
average	0.25	0.11	0.03	0.33	0.29
Analysis of variance					
water	*[b]	ns[b]	ns	*	ns
timing	ns	ns	ns	ns	ns
water × timing	ns	ns	*	*	ns
coefficient of variance	23.6	21.7	19.6	12.8	18.7

[a] DAT = days after transplanting

[b] * P<0.05, ** P<0.01, *** P<0.001; ns = nonsignificant (P>0.05).

Table 5. Recovery fraction of ^{15}N-enriched fertilizer N in microplots in 2003 with analysis of variance.

Treatment	Grain	Straw	Roots	Soil	Unaccounted for
aerobic					
basal	0.05	0.06	0.02	0.42	0.44
25 DAT[a]	0.09	0.08	0.04	0.26	0.53
45 DAT	0.14	0.14	0.04	0.25	0.43
average	0.09	0.09	0.04	0.31	0.47
flooded					
basal	0.11	0.08	0.02	0.21	0.58
25 DAT	0.18	0.13	0.02	0.24	0.42
45 DAT	0.30	0.28	0.02	0.19	0.20
average	0.20	0.17	0.02	0.22	0.40
Analysis of variance					
water	*[b]	ns[b]	*	ns	ns
timing	***	**	ns	ns	ns
water × timing	ns	ns	ns	ns	ns
coefficient of variance	13.3	20.3	16.1	16.1	17.1

[a] DAT = days after transplanting

[b] * P<0.05, ** P<0.01, *** P<0.001; ns = nonsignificant (P>0.05).

Table 6. Recovery fraction of ^{15}N-enriched fertilizer N per soil layer in microplots in 2002.

Treatment	0−5 cm	5−15 cm	15−30 cm
aerobic			
basal	0.12	0.07	0.02
25 DAT[a]	0.16	0.06	0.03
45 DAT	0.15	0.08	0.03
flooded			
basal	0.26	0.11	0.09
25 DAT	0.19	0.04	0.03
45 DAT	0.23	0.04	0.02
Analysis of variance			
water	**[b]	ns[b]	ns
timing	ns	ns	ns
water × timing	ns	ns	ns
coefficient of variance	14.0	36.1	49.5

[a] DAT = days after transplanting

[b] * P<0.05, ** P<0.01, *** P<0.001; ns = nonsignificant (P>0.05).

Table 7. Recovery fraction of ^{15}N-enriched fertilizer N per soil layer in microplots in 2003.

Treatment	0−5 cm	5−15 cm	15−30 cm
aerobic			
basal	0.20	0.10	0.10
25 DAT[a]	0.12	0.10	0.02
45 DAT	0.14	0.09	0.02
flooded			
basal	0.17	0.04	0.01
25 DAT	0.19	0.04	0.01
45 DAT	0.15	0.03	0.01
Analysis of variance			
water	ns[b]	**[b]	ns
timing	ns	ns	ns
water × timing	ns	ns	ns
coefficient of variance	12.5	25.7	75.8

[a] DAT = days after transplanting

[b] ns = nonsignificant (P>0.05); * P<0.05, ** P<0.01, *** P<0.001.

Table 8. Total N (kg ha^{-1}) per soil layer (cm) as determined in the microplots with pair-wise comparison for water regime.

Year	Water regime	0−5 cm	5−15 cm	15−30 cm
2002				
	aerobic	676	1388	1159
	flooded	700	1259	1571
Pair-wise comparison				
aerobic vs flooded		ns[a]	*[a]	ns
coefficient of variance		24.9	19.0	12.1
2003				
	aerobic	636	1210	1099
	flooded	602	1225	1159
Pair-wise comparison				
aerobic vs flooded		ns	ns	ns
coefficient of variance		14.2	9.8	15.9

[a] ns = nonsignificant (P>0.05); * P<0.05, ** P<0.01, *** P<0.001.

Averaged for both years, unaccounted ^{15}N fractions were higher in aerobic (0.47) plots than in flooded (0.35) plots.

There were some differences between N recovery obtained with the difference method in the main plots and N recovery as determined using ^{15}N in the microplots. Under aerobic conditions, the recoveries were about the same, whereas under flooded conditions, recoveries were 14% and 32% higher with the difference method than with the ^{15}N method. Higher values of N recovery with the difference method than with the ^{15}N method for rice were also reported by Schnier (1994), Cassman et al. (1993), and Bronson et al. (2000). Bronson et al. (2000) found that added N interaction through isotope substitution of the labile N pool was the reason for the discrepancy between the two methods in flooded soil. The N fraction not accounted for, measured with the ^{15}N method in our study, remains valid because N transformation processes (NH_3 volatilization, denitrification) will hardly be affected by pool substitution (Bronson et al., 2000).

In our study, biomass and total plant N were on average 15% lower in the microplots than in the main plots. Bufogle et al. (1997) also found lower biomass and total plant N for rice in microplots (of 75 × 75 cm) than in the main field.

Discussion

Aerobic rice was developed to reduce water input in the lowland rice system, while maintaining high yields and thereby increasing water productivity (WP_{I+R}). Achieving yields of 70−80% of attainable yields of non water limited lowland rice is still a challenging target for aerobic rice. Attainable yield of IR72, an elite lowland cultivar, without water limitation at 200 kg fertilizer N ha^{-1} in the same years and with the same sowing and transplanting dates as in our experiment, was calculated at 9.1 t ha^{-1} in 2002 and 8.8 t ha^{-1} in 2003 using the crop growth model ORYZA2000 (Bouman et al., 2001). This is in the range of the yield potential for IR72 in the dry season at IRRI which is 8−10 t ha^{-1} (Kropff et al., 1993). This potential, however, reflects the elite lowland cultivars, grown without water scarcity. The yield of Apo under aerobic conditions was 69% in 2002 and 48% in 2003 of that of IR72 with 200 kg N ha^{-1}. Irrigation water savings with Apo were 36% in 2002 and 41% in 2003 in the aerobic treatment as compared with the flooded treatment. Compared with IR72 with 200 kg N ha^{-1} without water limitation, WP_{I+R} would slightly increase in 2002 but decrease in 2003 for Apo under aerobic conditions. Also crop duration of Apo was 8−19 days longer than for IR72, thereby increasing water use. Higher levels of N fertilizer for Apo would increase the risk on lodging, because Apo is a rather tall (up to 140 cm) cultivar.

The absence of an effect of water regime on LAI, biomass, total plant N, and yield at 0-N suggests that indigenous soil N supply was nearly the same under aerobic and flooded conditions. It also suggests that, in 0-N aerobic plots, N limited growth more than water. In the 150-N plots, biomass, LAI, total plant N, N recovery, and grain yield were significantly lower under aerobic conditions than under flooded conditions. Despite the lower total plant N and apparent N recovery, the contents of leaf N and total plant N under aerobic conditions were nearly the same as under flooded conditions. Therefore, in 150-N aerobic plots, water limited growth more than N.

Beyrouty et al. (1994) compared crop growth and N dynamics in a field experiment with flooded and alternately submerged-nonsubmerged conditions in lowland rice with an N application rate of 150 kg ha^{-1}. Their threshold of soil water potential for re-flooding was also –30 kPa, and they found biomass and total plant N to decrease from panicle initiation onward, while N content in plant tissue remained unaffected. In our experiment, the 2002 season shows a similar pattern, whereas in 2003, biomass and total plant N in aerobic plots decreased before panicle initiation already. Beyrouty et al. (1994) also recorded no differences in total plant N content between alternately submerged-nonsubmerged and flooded rice. They gave two explanations for the reduced total plant N, that correspond with the findings in our experiment: (1) water stress reduced crop N demand and (2) soil conditions led to increased N losses via nitrification-denitrification and/or ammonia volatilization. The interaction between water regime and fertilizer N management was also studied in rainfed lowland rice systems. In this system, Wade et al. (1999) found that nutrient application (notably N) substantially increased yields only when water limitation was minimal.

The relatively low uptake of N under aerobic conditions (vs flooded conditions) was also reflected by the relatively low apparent N recovery under aerobic conditions. Of the 150 kg N ha^{-1} applied, only an average of 22% was taken up by the crop while 31% was left in the soil and roots after harvest. Since nitrate concentrations in groundwater and soil water were negligible, most of the 47% N unaccounted for must have left the system as gaseous-N losses promoted by rapid nitrification-denitrification processes. In our experiment, intensive weed control prevented growth reduction and N uptake by weeds, which might have caused further reduction in apparent N recovery of aerobic rice.

A higher apparent N recovery in aerobic rice than the 22% we found, is desirable and would not only increase N application efficiency, thereby reducing fertilizer costs to farmers, but would also reduce gaseous-N losses to the environment such as N_2O, which is a potent greenhouse gas. Since the amount of irrigation water determines yield under conditions when N is not limiting, we suggest combining water treatments with N treatments to optimize yield and resource-use efficiency. Fertilizer N application as basal just before transplanting showed the lowest N recovery. Further experiments should determine whether later timing of fertilizer N will increase N recovery. For the cultivar Apo, trials with a range of N levels are suggested for optimizing N application rates. High N recoveries of up to 0.6–0.7 kg kg^{-1} in arable cereal crops show that higher N recoveries in aerobic rice might be possible when N dose and timing better match the N requirement of the crop.

Currently, the yield potential of cultivars adapted to aerobic rice systems is much lower than that of modern lowland cultivars such as IR72 (the plants of Apo lodged at yields of around 7 t ha^{-1}). However, breeding programs may soon deliver higher yielding cultivars than Apo or other currently “most suitable” cultivars. When breeding programs develop germplasm for aerobic rice systems, these should replace Apo in the above proposed irrigation and N optimization trials to obtain higher yields.

The plant-water relationships that were established for the cultivar Apo correspond well with results obtained in SNS lowland rice systems under low to moderate water-stress levels. Both the results with Apo in our experiment, and reports of the behavior of lowland cultivars under SNS conditions, confirm water-stress effects at soil water potentials of 0 to −30 kPa (O’Toole and Baldia, 1982; Wopereis et al., 1996a; Bouman and Tuong, 2001; Lu et al., 2000; Belder et al., 2004). These water-stress effects express themselves through reduced leaf area development, reduced biomass growth, and reduced yield.

The lower biomass, LAI, total plant N, yield, and WP_{I+R} in 2003 than in 2002, could not be explained by the average soil water potential. A possible explanation could be the later timing of lowering the threshold to −10 kPa in 2003 than in 2002. The later imposition could have caused extra stress for the crop just before flowering. Further improvements should be made in water regimes in aerobic rice systems to reduce crop water stress.

The difference between 2002 and 2003 could also have been caused by sustainability problems of continuously or repeatedly growing of aerobic rice (even though there was a break crop of flooded rice in between the dry seasons of 2002 and 2003). Sustainability problems with monocropping of rice under aerobic conditions have been reported by George et al. (2002) for the Philippines and by Wang et al. (2002) for China. The reason for possible yield decline is not known yet, though the build up of soil-borne pathogens such as nematodes is a likely candidate (Lafitte et al., 2002). Another reason might have been a decline in soil organic matter under aerobic cultivation. However, such decline was not likely in our experiments, because total soil N at physiological maturity in the microplots was not significantly lower in aerobic than in continuously flooded soil in both 2002 and 2003 (Table 8). Since soil-extractable NO_3+NH_4 (data not shown) did not constitute more than 0.2% of total N at physiological maturity, almost all N was in organic form. Assuming that C:N ratios were not different between flooded and aerobic soils leads us to the conclusion that soil organic matter content did not differ between the two water regimes after both seasons. We did not investigate total N under continuous aerobic cropping. There could be a decline in soil organic matter under this system as compared with permanent flooding or the rotation flooded rice - aerobic rice. The reduction in yield under continuous aerobic rice cropping should be further investigated and remedial measures developed.

Aside from the crop-water-nitrogen management issues, the feasibility of aerobic rice also depends on socio-economic factors such as farmers' income, temporal water availability, water pricing, and food demand. Feasibility of aerobic rice in uplands depends on availability of supplementary irrigation and inputs such as fertilizers and herbicides. Moreover, with increasing water shortage, other crops with less drought sensitivity may be more suitable and replace rice.

Acknowledgments

The research reported here contributes to the Comprehensive Assessment of Water Management in Agriculture, supported by the Dutch Government, through the project 'Potentials of water-saving technologies in rice production: an inventory and synthesis of options.' We are grateful to Stephan Haefele and Tanguy Lafarge from IRRI for their valuable comments on earlier versions of this chapter.

CHAPTER 5

Exploring options for water savings in lowland rice using a modelling approach

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Abstract
Water-saving irrigation regimes are needed to deal with a reduced availability of water for rice production. Two important water-saving technologies at field scale are alternately submerged-nonsubmerged (SNS) and flush irrigated (FI) rice. SNS allows dry periods between submerged soil conditions, whereas FI resembles the irrigation regime of an upland crop. The effects of these regimes on water balance and water savings were compared with continuously submerged (CS) and rainfed (RF) regimes.
The crop growth model ORYZA2000 was used to calculate seasonal water balances of CS, SNS, FI, and RF regimes for two locations: Tuanlin in Hubei province in China from 1999–2002 during summer seasons and Los Baños in the Philippines in 2002–2003 during dry seasons. The model was first parameterized for site-specific soil conditions and cultivar traits and then evaluated using a combination of statistical and visual comparisons of observed and simulated variables. ORYZA2000 accurately simulated the crop variables leaf area index, biomass, and yield, and the soil water balance variables field water level and soil water tension in the root zone.
Next, a scenario study was done to analyse the effect of water regime, soil permeability, and groundwater table depth on irrigation requirement and associated rice yield. For this study historical weather data for both sites were used.
Within years, the amount of irrigation water application was higher for CS than for the water-saving regimes. It was found that groundwater table depth strongly affected the water-yield relationship for the water-saving regimes. Rainfed rice did not lead to significant yield reductions at Tuanlin as long as the groundwater table depth was less than 20 cm. Simulations at Los Baños with a more drought tolerant cultivar showed that FI resulted in higher yields than RF thereby requiring only 420 mm of irrigation.
The soil type determines the irrigation water requirement in CS and SNS regimes. The more permeable soil requires around 2000 mm of irrigation water whereas slowly conducive soils require less than half given the local weather and cultivar characteristics. We conclude that water savings can be considerable when water regimes are adapted to soil characteristics and rainfall dynamics. To optimize water saving regimes, groundwater table depth and soil permeability should be taken into account.

Keywords: Irrigation, water balance, percolation, groundwater depth, soil permeability.

Introduction

Increasing water scarcity necessitates the development of water-saving technologies in rice production that depart from continuous submergence (CS) where the soil is saturated and anaerobic from crop establishment to close to harvest. Two important water-saving strategies in irrigated lowland rice are emerging: (i) 'alternate submergence-nonsubmergence' (SNS), which is also called 'intermittent irrigation' or 'alternate wetting-and-drying', and (ii) 'aerobic rice' (Tuong and Bouman, 2003). In SNS, irrigation is applied a few days after water has disappeared from the surface so that periods of submerged soil conditions alternate with periods of nonsubmerged soil conditions during the whole growing season. The SNS technology has been researched extensively in countries such as China and the Philippines, and has been shown to maintain yields close to those obtained under continuously flooded conditions while using some 15-30% less water (Li, 2001; Tabbal et al., 2002; Singh et al., 2001; Li and Barker, 2004). In aerobic systems, special aerobic rice varieties are grown in nonsubmerged and nonsaturated aerobic soil (just like an upland crop such as wheat or maize) with supplementary irrigation and sufficient external inputs to reach high yields. Aerobic rice is targeted at water-short irrigated environments where the availability of water is too low to grow rice under SNS regimes. Although the concept of aerobic rice is relatively new, initial research in China and the Philippines suggests that yields of around 70% of that realized under CS can be obtained using about 50% of the water used in continuously flooded systems (Bouman et al., 2005; Yang et al., 2005). Most research on SNS and aerobic rice so far has been limited to individual field experiments, and it has been suggested that simulation models should be applied to synthesize experimental findings and extrapolate them to different environments and agro-ecological conditions (Bouman and Tuong, 2001; Belder et al., 2005a).

Another aspect of water-saving technologies that needs further investigation is the true nature of water savings that can be realized. Water-saving technologies such as SNS and aerobic rice aim at reducing so-called nonproductive water losses from paddy fields, such as percolation and evaporation (Tuong and Bouman, 2003). However, water that is lost by percolation enters the groundwater and may be re-used downstream by pumping or capturing groundwater when it enters the surface water system. Therefore, Seckler (1996) argued that only reductions in water flows that can't be reused downstream such as evaporation and transpiration, or flows to sinks such as saline aquifers or seas, are 'real' water savings. On the other hand, Guerra et al. (1998) argued that re-use of percolation water involves water development which involves labour, capital, and energy costs such as for pumping. They also argued that water recovery is not always possible when it is needed and although percolation losses may be re-usable at a regional scale, they do represent a real water loss to individual farmers with associated negative impacts on (water) costs or yield loss (in case of water scarcity at the field level). An analysis of the water balance at field scale is needed to provide insight in the magnitudes of the different water outflows from paddy fields under water-saving technologies such as SNS and aerobic rice. Since components of the water balance are not easily measured, a modelling approach can be helpful.

Adoption of water-saving technologies may have impact on environmental conditions that may have repercussions on the performance of these water-saving technologies themselves. Cabangon et al. (2004) and Belder et al. (2005a) observed that groundwater table depths were shallow (around 0-30 cm) in various water-saving field experiments in typical lowland rice growing areas in China and the Philippines. Under these conditions, the soil remained close to saturation even under SNS regimes, and the rice crop benefited from direct water uptake from the shallow groundwater and from capillary rise. Yields under SNS conditions in these field experiments were at par with yields under continuously flooded conditions. However, a large-scale adoption of water-saving technologies such as SNS and aerobic rice, could lead to a drop in groundwater table depth because of the reduction in percolation flows under these water-saving conditions (Mishra et al., 1990; Singh et al., 2001). A lower groundwater table depth may negatively affect water availability to the crop and hence decrease yield, and it may affect the magnitudes of the components of the water balance such as percolation and evaporation.

In this chapter, we study and compare the yield, water use and water balance components (evaporation, transpiration and percolation) of three water-saving technologies in comparison with continuous submergence, and investigate the effects of changes in environmental conditions (weather, soil properties and groundwater depth) using a combined experimental-modelling approach. We analysed two sets of field experiments with four water-saving technologies – continuously submerged, alternately submerged-nonsubmerged, rainfed, and aerobic flush irrigated – that were conducted in China and the Philippines. Using measured crop and soil water variables, we calibrated and evaluated the crop growth model ORYZA2000 (Bouman et al., 2001), and then used the model to determine in detail the parameters of the water balance of the field experiments. Next, we used the model to extrapolate the results of the field experiments in time using historic weather data, and to explore the effects of differences in soil hydrological properties and of changes in groundwater table depth.

Materials and methods

Methodological framework

We used data from two sets of field experiments on continuously submerged, submerged-nonsubmerged, and aerobic rice. One series of experiments was done at Los Baños, the Philippines, and the other one at Tuanlin, near Wuhan, in China. Both experiments included two levels of nitrogen (N), a control and a supposedly optimum agronomic level. We parameterized and evaluated the ORYZA2000 model using the experimental crop and soil data of those field experiments. Both experimental data and simulation results were used to analyse the components of the water balance and yield stability. Next, the model was used to extrapolate our findings to two soil types and a range of groundwater table depths and weather conditions.

Field experiments

At Tuanlin (30°52′ N, 112°11′ E) in Hubei province, China, experiments were done during summer seasons on a silty clay loam of the experimental station of the Zhanghe Irrigation System. Two hybrid cultivars were used: 2You501 in 1999 and 2You725 in 2000-2002. The experiments were laid out in a split-plot design with four replicates, with water regimes in the main plot and N levels in the subplot. The water regimes were: continuously submerged (CS), alternately submerged-nonsubmerged (SNS), rainfed (RF), and flush irrigation (FI). The N treatments were 0 and 180 kg N ha^{-1} (locally recommended to obtain no N-limited yields). The 180 kg N was applied as 30% basal, 30% 10 days after transplanting (DAT), 30% at panicle initiation, and 10% at flowering. In all treatments, 29-44-days-old seedlings were transplanted at the rate of 2 seedlings per hill and 25 hills m^{-2}. P and K fertilizers were applied just before transplanting at rates of 25 and 70 kg ha^{-1} for P and 70 kg ha^{-1} for K.

The CS, SNS and RF plots were puddled, whereas the FI plots were dry-ploughed and harrowed. In SNS plots, the periods without submergence usually lasted 4–5 days, depending on rainfall conditions, with a special ‘mid-season drainage’ period of 7–12 days just before panicle initiation. The RF plots were kept submerged during the first two weeks after transplanting and were only irrigated when fertilizer N was applied. FI plots were irrigated when the soil water tension went up above 30 and 50 kPa, except in 2001 when no tensiometers were installed. In this year, the irrigation application was based on the occurrence of cracks in the soil.

In 2001, plastic sheets were installed in the bunds between plots with different water regimes to 0.3 m deep to prevent seepage flows. In 2002, a deep drain of 1.0 m depth was excavated around the main plots to increase internal drainage and lower the groundwater table.

At Los Baños (14°18′ N, 121°25′ E), Philippines, experiments were done on a clay soil of the experimental farm of the International Rice Research Institute (IRRI). The improved upland cultivar 'Apo' was grown in the dry seasons of 2002 and 2003. The experiments were laid out in a split-plot design with four replicates, with water regimes in the main plot and N levels in the subplot. The water treatments were continuously submerged (CS) and aerobic with flush irrigation (FI). The N treatments were 0 and 150 kg N ha^{-1}, with the 150 kg N applied in three equal applications at basal, 25 DAT, and 45 DAT. P, K and Zn were applied as basal at 60 kg ha^{-1}, 40 kg ha^{-1} and 5 kg ha^{-1}, respectively.

Like at Tuanlin, the CS plots were puddled, and the FI plots were dry-ploughed and harrowed. FI plots were irrigated when the soil water tension at 15 cm depth dropped below −30 kPa during the whole growing season, except for a period of a week around flowering when irrigation was applied at −10 kPa. Plastic sheets were installed in the bunds between the main plots down to 0.3 m depth. Moreover, each main plot was surrounded by a double interceptor drain of 0.4 m deep. In all treatments, 20-24-days-old seedlings from wet-bed nurseries were transplanted at 3 seedlings per hill at a spacing of 25 × 10 cm.

The amount of irrigation water applied was monitored at each irrigation from transplanting till maturity, by using flow meters (installed in the flexible hoses used for irrigation) at Tuanlin and V-notch weirs at Los Baños. In FI plots, gauged tensiometers were installed at 15-20 cm depth except for Tuanlin in 2001 and readings were made daily. In all except the FI plots, field water levels were daily measured using 30-cm-high perforated PVC pipes installed in each plot. At Los Baños, the groundwater table depth was measured daily in fully perforated, 5-cm diameter PVC pipes installed down to 1.75 or 2.0 m in the centre of the bunds between the main plots. At Tuanlin, groundwater table depth was determined only in 2001 and 2002 in bunds separating replicates using 5-cm diameter PVC pipes as was done at Los Baños. Daily weather data, including rainfall, maximum and minimum air temperature, sunshine hours (at Tuanlin), radiation (at Los Baños), wind speed, and relative humidity were measured with on-site meteorological stations.

At both Tuanlin and Los Baños, crop samples were taken at key growth stages (transplanting, mid-tillering, panicle initiation, flowering, mid-grain filling, physiological maturity) to determine total crop biomass and leaf area index (LAI). At Tuanlin, 12-hill plant samples were taken, and at Los Baños, 20-hill plant samples were taken, both representing 0.50 m^2. Biomass was determined after oven-drying at 70 °C to constant weight. At Tuanlin, leaf surface areas were manually determined and at Los Baños, the LAI was determined using a Licor LI 3100 area meter. At maturity, yield was determined from one central 4.8-m^2 area at Tuanlin, and from two central

5.0-m^2 areas at Los Baños, and expressed at 14% moisture content. At both sites soil water retention characteristics were determined in several soil layers.

Table 1 summarizes some key characteristics of each experiment. More details of the experiments are presented by Belder et al. (2004, 2005a) and Cabangon et al. (2001) for Tuanlin, and by Belder et al. (2005b) and Bouman et al. (2005) for Los Baños.

ORYZA2000 model

Model description ORYZA2000 is an explanatory and dynamic eco-physiological simulation model of the 'School of De Wit' (Bouman et al., 1996; Van Ittersum et al., 2003). It simulates growth and development of rice in situations of potential production, water limitations, and nitrogen limitations. It is assumed that, in all these production situations, the control of diseases, pests, and weeds is optimal. A detailed explanation of the model and the program code is given by Bouman et al. (2001). A description of ORYZA2000 for potential and N limitations is given by Bouman and Van Laar (2005), who also validated the model for a range of N-levels at Los Baños using five seasons of experimental data. The soil water balance model PADDY and the crop-water relations were summarized by Boling et al. (2005), who demonstrated that the model worked well under irrigated and rainfed conditions, at various levels of N fertilization, using eight seasons of experimental data at Jakenan, Indonesia.

Parameterization ORYZA2000 was parameterized for the rice cultivars used in our experiments, starting with the standard crop parameters for cultivar IR72 and following the procedures set out by Bouman et al. (2001). First, development rates were calculated using observed dates of emergence, panicle initiation, flowering, and physiological maturity. Next, specific leaf area was calculated from the measured values of leaf area and leaf dry weight. The partitioning of assimilates was derived from our measured data on the biomass of leaf blade, stem plus leaf sheath, and panicles but did not significantly differ from IR72. Leaf stress parameters were parameterized by Wopereis et al. (1996a). In this study, we calibrated the values for minimum and maximum soil water tension to allow non-limited and complete inhibition of leaf expansion. For each experiment with submerged conditions (CS, SNS), the average percolation rate was first estimated from a water balance calculation and from daily measurements of field water level, and then fine-tuned by model fitting (fine-tuning the parameter value until simulated field water levels agreed best with measured field water levels). For nonsubmerged conditions, the Van Genuchten equations were used to describe the soil water retention and conductivity

Table 1. Experimental details of the field experiments.

Experiments		Treatments		Cropping data				Other nutrient applications		
Site	Year	Water regimes[a]	N rates ($kg\ ha^{-1}$)	Cultivar	Emergence date	Transplanting date	Growing season[b] (days)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	Zn ($kg\ ha^{-1}$)
China										
Tuanlin	1999	CS, SNS	180	2You501	21 April	20 May	114–115	25	70	-
	2000	CS, SNS	0 and 180	2You725	14 April	18 May	109–113	25	70	-
	2001	SNS, RF, FI,	0 and 180	2You725	16 April	24–28 May	105–109	70	70	-
	2002	SNS, FI-30, FI-50	0 and 180	2You725	22 April	29 May	109–110	70	70	-
Los Baños	2002	CS, FI	0 and 150	IR55423-01	6 January	24 January	102–113	60	40	5
	2003	CS, FI	0 and 150	IR55423-01	12 January	4 February	100-105	60	40	5

[a] CS=continuously submerged
SNS=alternately submerged-nonsubmerged
RF=partially rainfed
FI= flush irrigation
FI-30=flush irrigation with threshold in soil water tension of 30 kPa (see Chapter 3)
FI-50=flush irrigation with threshold in soil water tension of 50 kPa (see Chapter 3)

[b] From transplanting till physiological maturity.

characteristics in the PADDY water balance model. The Van Genuchten parameters were calculated with the pedotransfer functions developed by Wösten et al. (2001), using the measured soil texture and soil organic matter content data at the sites (Table 2). For both Tuanlin and Los Baños, the value for the saturated conductivity (K_{sat}) of the least permeable layer (plough pan) was further fine-tuned by matching simulated and measured field water levels and soil water tensions. The indigenous soil N supply was first estimated from crop N uptake in zero-N treatments, and subsequently fine-tuned by model fitting.

For each experimental year, the daily groundwater depth and weather data were directly taken from the measurements. For Tuanlin in 1999 and 2000, a fixed groundwater table depth of 40 cm was assumed based on groundwater observations in the other years, although recorded field water levels indicated perched water tables of less than 15 cm during a large part of the growing seasons.

Evaluation Following the procedures set out by Bouman and Van Laar (2005), we used a combination of graphical presentations and statistical measures to evaluate the performance of ORYZA2000 in simulating our experimental data. We graphically compared the simulated and measured soil water tension, field water level, LAI, biomass, and yields. For the same variables, we computed the slope (α), intercept (β), and coefficient of determination R^2 of the linear regression between measured (X) and simulated (Y) values. We also calculated the absolute ($RMSE_a$) and normalized ($RMSE_n$) root mean square errors between simulated and measured values, and compared these with the standard errors of the measured variables. The variation in measured data is represented by mean standard deviation and mean coefficient of variation.

Scenarios We used ORYZA2000 to extrapolate the experimental conditions in time using 14 years of weather data for Tuanlin (1989–2002) and 25 years of weather data for Los Baños (1979–2003). Different hydrological conditions were mimicked by three groundwater table depths: 20-, 60-, and 100-cm below the surface. Two soil types were constructed based on the parameterized values in our data set of the percolation rate of the ponded water layer and the K_{sat} of the plough pan. The first soil type had a percolation rate of 4.0 mm d^{-1} and a K_{sat} of the plough pan of 3 mm d^{-1}, and is referred to as ‘impermeable’. The second soil is labelled ‘permeable’ and had a percolation rate of 14.0 mm d^{-1} and a K_{sat} of the plough pan of 30 mm d^{-1}. The water regimes CS, SNS, RF, and FI, were simulated for all combinations of soil type and groundwater table with the available historic weather data. In the CS regime, irrigation water was applied (by the model) each time the field water level dropped to

Table 2. Soil water retention characteristics, saturated hydraulic conductivity, and parameterized Van Genuchten parameters per soil layer at Tuanlin and Los Baños.

Soil depth	Water content			Van Genuchten parameters[a]			
	Saturation ($cm^3\ cm^{-3}$)	Field capacity ($cm^3\ cm^{-3}$)	Wilting point ($cm^3\ cm^{-3}$)	VGA (cm^{-1})	VGL (-)	VGN (-)	VGR ($cm^3\ cm^{-3}$)
Tuanlin							
0-15	0.55	0.46	0.32	0.075	–4.6	1.10	0.01
15-20	0.54	0.46	0.32	0.037	–5.2	1.11	0.01
20-30	0.54	0.46	0.32	0.037	–5.2	1.11	0.01
30-60	0.54	0.46	0.32	0.038	–5.3	1.11	0.01
60-100	0.54	0.46	0.33	0.018	–5.1	1.13	0.01
Los Baños							
0-10	0.52	0.48	0.21	0.127	–6.2	1.12	0.01
10-15	0.52	0.48	0.21	0.127	–6.2	1.12	0.01
15-30	0.55	0.47	0.21	0.047	–0.6	1.10	0.01
30-60	0.61	0.52	0.21	0.078	–4.9	1.08	0.01
60-80	0.64	0.58	0.21	0.032	–11.1	1.07	0.01

[a] Source: Van Genuchten (1980) and Van Genuchten et al. (1991):

$$S = (\theta - VGR)/(\theta_s - VGR) = [\ 1 + |VGL\ h|^{VGN}\ ]^{-m}$$

$$K(S) = K_s S^{VGL}[1 - S^{1/m})^m]^2$$

where:

S	degree of saturation	-
θ_s	saturated values of volumetric water content θ	$cm^3\ cm^{-3}$
h	is soil pressure potential	kPa
m	1 –1/VGN	-
K_s	saturated hydraulic conductivity	$cm\ d^{-1}$
VGA	Van Genuchten *alpha* parameter	cm^{-1}
VGL	Van Genuchten *lambda* parameter	-
VGN	Van Genuchten *n* parameter	-
VGR	Van Genuchten residual water content	$cm^3\ cm^{-3}$

10 mm. In the SNS and the FI regimes, irrigation water was applied each time the soil water tension at 10–15 cm depth reached 0.5 kPa and 50 kPa, respectively. The amount of irrigation was 60 mm per event. No irrigation was applied in the RF regime. The soil was puddled in the CS, SNS and RF regimes, and non-puddled in the FI regime. In all scenarios, the fertilizer N rate was 180 kg N ha^{-1} at Tuanlin and 150 kg N ha^{-1} at Los Baños.

Water balance analysis

In this study, we defined the seasonal water balance as:

$$\sum (I + R + C) = \sum (E + T + P + D) + \Delta W \quad \text{(mm)} \qquad (1)$$

where I is irrigation, R is rainfall, C is capillary rise, E is evaporation, T is transpiration, P is percolation, and D is overbund drainage (all in mm d^{-1}), and ΔW is the difference in soil water storage (mm). On a seasonal basis, the in- and outflow rates are summed from transplanting till physiological maturity. Irrigation, rainfall and drainage were directly measured. The evaporation, transpiration, capillary rise, percolation, and the difference in water storage were calculated with ORYZA2000. The difference in storage was calculated as the difference in field water level at transplanting and at physiological maturity, plus the difference in water content in the root zone at transplanting and at physiological maturity. In ORYZA2000, the actual evaporation and transpiration rates are calculated using Penman-Monteith equations (Penman, 1948; Monteith, 1969) and feedback mechanisms between evaporation and transpiration on the one hand and soil water content on the other (see Bouman et al. (2001) for more details).

Results

Parameterization and evaluation of ORYZA2000

Parameterization The parameterized soil hydraulic properties are given in Table 3 (the complete set of all crop and soil parameter values is available from the authors on request). The average percolation rate of the soil varied between 1.6 and 15.1 mm d^{-1}. The highest values were found at Tuanlin in 2002, where the deep drain promoted rapid vertical water movement through the soil. All percolation rates of individual replicates were within the 0–26 mm d^{-1} range of values reported in literature for puddled rice fields (Wickham and Singh, 1978; Tabbal et al., 2002). For Tuanlin in 1999 and 2000, the percolation rates of SNS fields (only during periods of ponded water when continuous percolation occurred) was about twice as high as that of the CS fields.

The value of K_{sat} of the plough pan varied between 0.4 and 50 mm d^{-1}, and was well in the range of values presented by Wopereis et al. (1996b). High percolation rates were matched by high values of K_{sat}.

Evaluation The goodness-of-fit parameters between simulated and measured crop and soil water balance variables are presented in Tables 4 and 5. The simulated crop

Table 3. Calibrated parameter values in ORYZA2000: Percolation rate and saturated hydraulic conductivity of most impermeable layer.

Experimental data		Calibrated parameters	
Location and season	Water regime[a]	Percolation rate of ponded water (mm d^{-1})	Saturated hydraulic conductivity of most impermeable layer (mm d^{-1})
Tuanlin			
1999	CS	3.3	0.4
	SNS	5.1	10
2000	CS	2.3	3
	SNS	4.9	3
2001	SNS	4.5	32
	RF	1.6	2
	FI	NA[b]	2
2002	SNS	15.1	50
	RF	13.1	20
	FI	NA	30
Los Baños			
2002	CS	4.8	8
	FI	NA	20
2003	CS	5.9	8
	FI	NA	7

[a] CS=continuously submerged RF=rainfed
SNS=alternately submerged-nonsubmerged FI= flush irrigation
[b] NA=not applicable

variables were not significantly different from observed values with the Student's t-test, and R^2 values of the linear regression between observed and simulated values were at least 0.71. In Figure 1, simulated versus measured biomass data are presented for all experiments and treatments combined with a 1:1 line. The $RMSE_a$ for biomass was higher at Tuanlin than at Los Baños, whereas the coefficient of determination was high ($R^2 \geq 0.96$) at both locations. The simulated LAI deviated relatively more from observed values than was the case for total biomass. This was due to an overestimation of LAI in the control treatment. For LAI, α and β values deviated more from 1 and 0, respectively, the R^2 was only 0.78–0.85, and the $RMSE_n$ was relatively high with 45%.

A comparison between the course of simulated and measured field water levels I presented in Figure 2 for Tuanlin in 2000 (CS and SNS) and for Los Baños in 2002 (CS). Especially CS regimes showed a good match in all seasons. For SNS and RF

Table 4. Results of statistical comparison between observed and simulated biomass, leaf area index, grain yield, field water level, and soil water potential for Tuanlin and Los Baños.

Location	Water regime	Model variable	N	X_{mean} (SD)	Y_{mean} (SD)	P(t*)	α	β	R^2	$RMSE_a$	$RMSE_n$ (%)
Tuanlin											
	CS, SNS, RF, FI	Biomass (kg ha^{-1})	94	6896 (5923)	6465 (5620)	0.30	0.93	69	0.96	1321	19
	CS, SNS, RF, FI	Leaf Area Index (-)	102	3.06 (2.70)	3.60 (2.88)	0.09	0.96	0.66	0.80	1.38	45
	CS, SNS, RF, FI	Grain yield (kg ha^{-1})	22	7007 (1663)	6858 (1568)	0.44	0.79	1371	0.71	894	13
Los Baños											
	CS, FI	Biomass (kg ha^{-1})	60	4594 (4689)	4613 (4580)	0.49	0.97	161	0.98	590	13
	CS, FI	Leaf Area Index (-)	56	1.63 (1.67)	1.77 (1.31)	0.31	0.72	0.60	0.83	0.73	45
	CS, FI	Grain yield (kg ha^{-1})	8	4925 (1596)	5114 (2039)	0.42	1.23	–944	0.93	646	13
Tuanlin											
	CS	Field water level (mm)	195	48 (21)	49 (20)	0.31	0.89	6	0.82	9	19
	SNS	Field water level (mm)	182	40 (20)	40 (21)	0.49	0.70	12	0.42	17	43
Los Baños											
	CS	Field water level (mm)	55	37 (16)	40 (14)	0.12	0.44	24	0.26	15	42
Tuanlin											
	RF, FI	Soil water potential (kPa)	373	16 (15)	15 (13)	0.12	0.47	8	0.29	13	77
Los Baños											
	FI	Soil water potential (kPa)	178	8 (6)	10 (11)	0.00	1.26	1	0.52	8	107

N = number of data pairs; X_{mean} = mean of measured values; CV_{mean} = mean of coefficient of variation of measured values (%); Y_{mean} = mean of simulated values; SD = standard deviation; P(t) = significance of paired t-test; P(t) > 0.05 means simulated and measured values are the same at 95% confidence level; α = slope of linear relation between simulated and measured values; β = intercept of linear relation between simulated and measured values; R^2 = coefficient of determination of $Y = \alpha X + \beta$; $RMSE_a$ = absolute root mean square error; $RMSE_n$ = normalized root mean square error (%); NA= not applicable.

Table 5. Standard deviation (same unit as variable) and coefficient of variation (CV, %) of crop variables.

Crop variable	N[a]	SD	CV (%)
Tuanlin (CS, SNS, RF, FI)			
Biomass (kg ha^{-1})	94	658	14
Leaf Area Index (-)	102	0.40	18
Grain yield (kg ha^{-1})	22	488	8
Los Baños (CS, FI)			
Biomass (kg ha^{-1})	60	793	19
Leaf Area Index (-)	56	0.42	24
Grain yield (kg ha^{-1})	8	533	11

[a] N is number of data pairs
CS=continuously submerged RF=rainfed
SNS=alternately submerged-nonsubmerged FI=flush irrigation

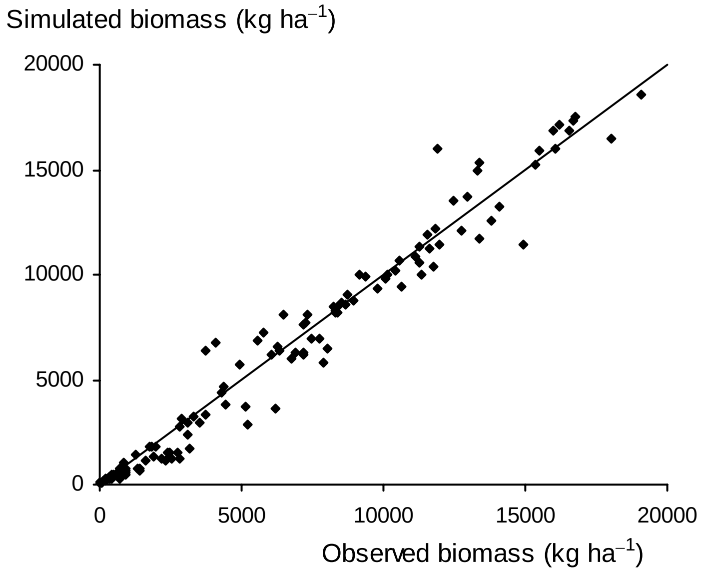

Figure 1. Evaluation of simulated and observed biomass with 1:1 line of all experiments at Tuanlin and Los Baños.

regimes (latter one not shown), small deviations occurred, especially at moments of re-irrigation after a period of nonsubmergence. Given the daily percolation rates of 2-15 mm, the $RMSE_a$ for field water level of 9–17 mm showed good simulation results over a range of observed field water levels of 0 to 125 mm. An example of simulated and observed values of soil water tension is given in Figure 3 for the FI treatment in Tuanlin in 2002, and for the FI treatment at Los Baños in 2002. Both graphs show a good agreement between simulated and observed values.

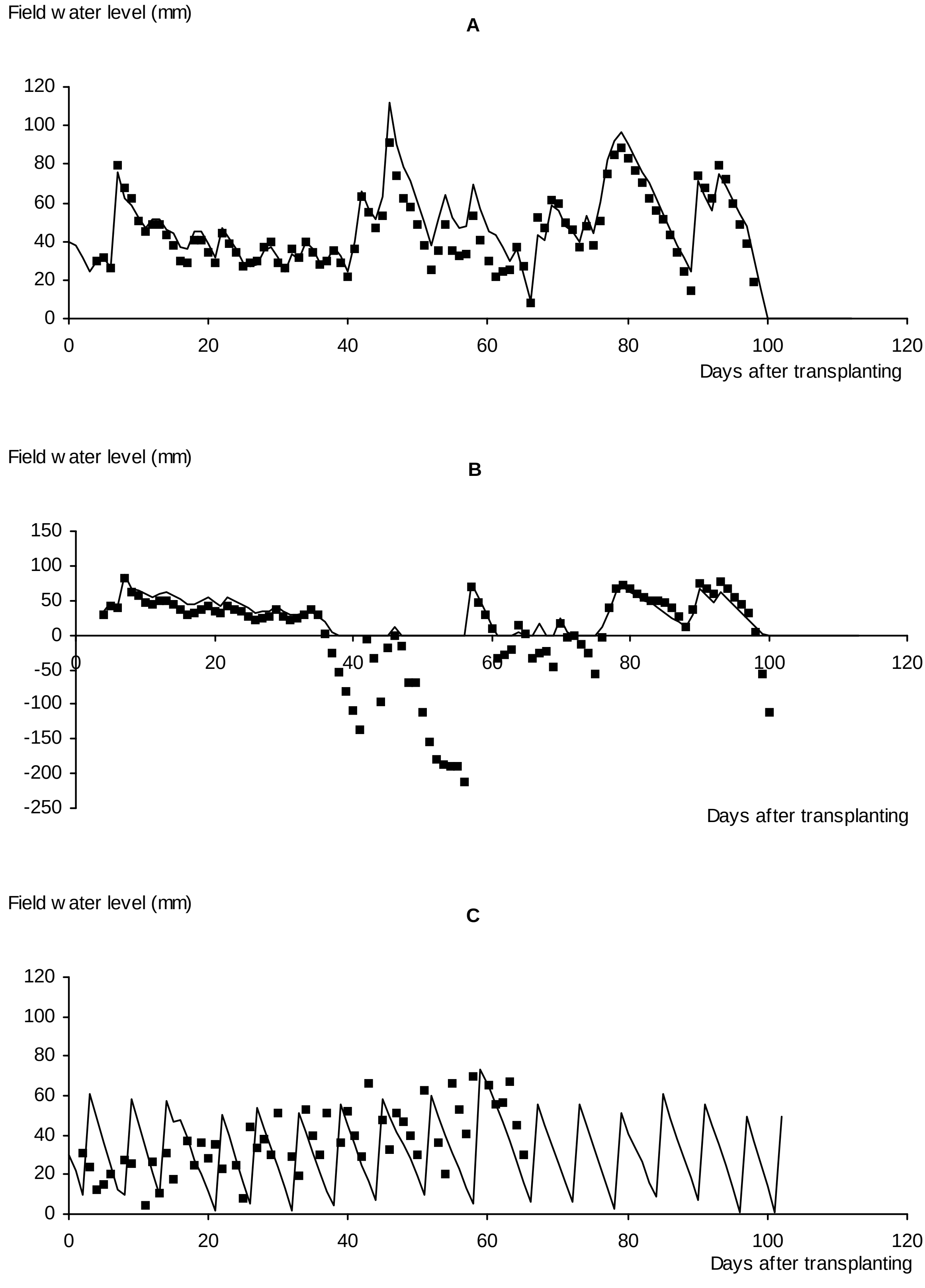

Figure 2. Simulated and observed field water levels in time for (A) the CS regime at Tuanlin in 2000, (B) the SNS regime at Tuanlin in 2000, and (C) the CS regime at Los Baños in 2002.

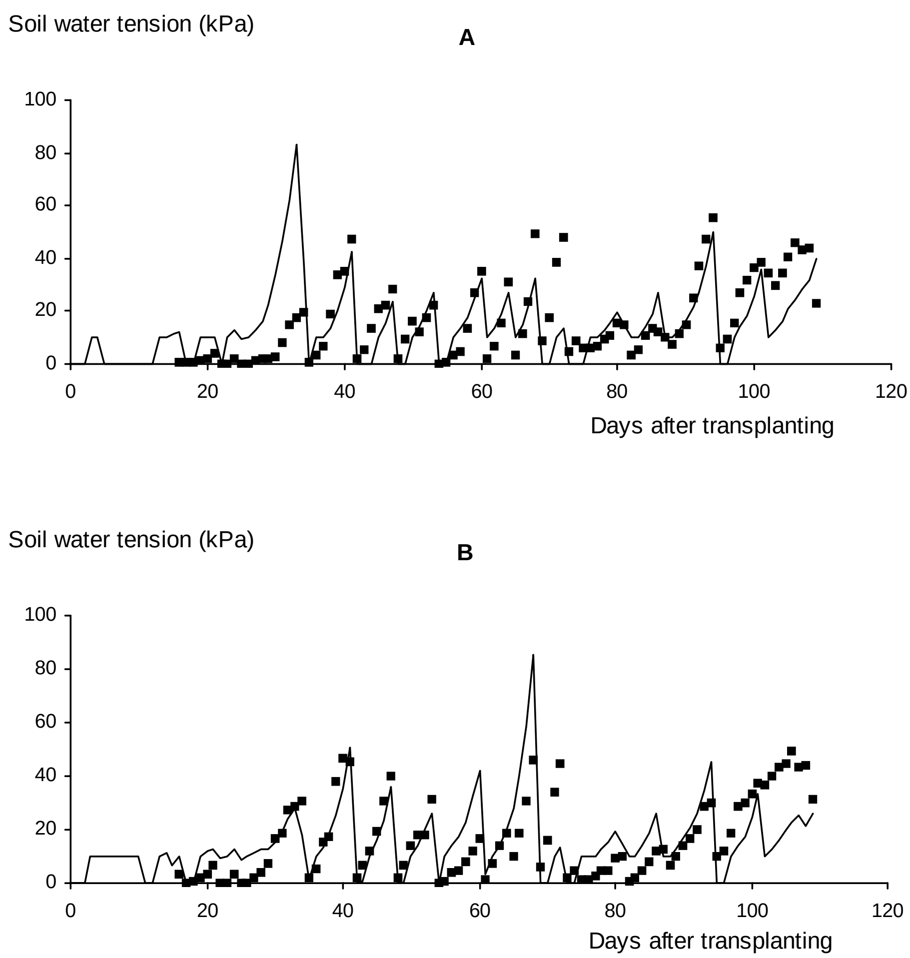

Figure 3. Simulated and observed soil water tension at 15 cm depth in time for (A) the FI regime at Tuanlin in 2002, and (B) the FI regime at Los Baños in 2002.

The agreement between simulated and observed field water depth and soil water tension was less strong than for the crop variables: the R^2 was lower, the slope α was not close to 1, and the intercept β deviated from 0. The $RMSE_n$ of soil water tension was even 77% for Tuanlin and 107% for Los Baños. These simulation results are explained by the fact that ORYZA2000 uses a simulation time step of one day. Rainfall can occur at any time during the day or night, but ORYZA2000 always assumes rainfall to have taken place during the day (the integration of the state variables always takes place at the end of each day). Similarly, irrigation during the field experiments took place any time of the day. With early morning applications, a considerable amount of water applied would already have been lost through evapotranspiration and percolation by the end of the day. With late afternoon application, less water would have been lost by the end of the day. In ORYZA2000, each irrigation application is treated as a one time input just before the integration of state variables. For field water depth, for example, this means that differences between simulated and observed values in the order of combined daily evapotranspiration and percolation rates (up to 10 mm d^{-1}) are to be expected (compare with $RMSE_a$ values for field water depth of 9–17 mm d^{-1}). Given this limitation of one-day time step integration, and the good graphical comparison between simulated and observed soil water variables, we concluded that the ORYZA2000 model simulates crop and soil water variables well enough to calculate the water balance and yield under the experimental conditions, and to extrapolate to different seasons and soil types.

Water balance of the field experiments

The water balance components of the field experiments are presented in Table 6. Rainfall varied between 297 and 448 mm at Tuanlin, and between 50 and 92 mm at Los Baños. The amounts of irrigation water applied varied between 36 mm (in the RF 0-N treatment at Tuanlin in 2001) and 1238 mm (in the SNS regime in 2002 at Tuanlin). Within years, water-saving regimes used less irrigation water than CS regimes.

Evaporation depended mostly on water regime and amount of N fertilizer applied, and ranged from 89 to 276 mm. Transpiration ranged from 288 to 508 mm and reflected canopy development and biomass growth being strongly affected by N level. The difference in soil water storage was generally larger at Tuanlin (up to 134 mm) because of higher field water levels at transplanting and earlier final drainage than at Los Baños. The seasonal amount of percolation varied between −98 to +1214 mm. Negative values mean that there was a net upward flow of water from deeper soil layers into the root zone, or that crops were able to take up water directly from shallow ground water tables. This net upward flux of water occurred at Tuanlin in the RF and the FI regimes in 2001. Here, the groundwater table was shallow and was continuously recharged by percolating water from the submerged plots surrounding the RF and FI plots. The highest amount of percolation was found at Tuanlin in 2002 when the deep drains were constructed that promoted internal soil drainage. Within seasons, the amount of percolation was higher for the CS regime than for the water-saving regimes, but differences between seasons were often larger. Capillary rise into the root zone was relatively small and ranged between 0 and 65 mm.

Scenario analysis

Table 7 summarizes the water balance components from the scenario runs. Since irrigation took place until the end of the season, we neglected the change in water storage. The presented percolation data are net percolation sums that include upward flows by capillary rise and upward flows from deeper soil layers into the root zone. Negative values indicate a net upward water flux and positive values indicate a net downward flux.

Table 6. Water balances as calculated with ORYZA2000 for Tuanlin and Los Baños.

Location	Year	Water regime[a]	N level	Measured components		Simulated components				
				Irrigation	Rainfall	Evaporatior	Δ Storage	Percolation	Capillary rise	Transpiration
			($kg\ ha^{-1}$)	(mm)		(mm)				
Tuanlin	1999	CS	180	451	377	149	78	352	36	441
		SNS	180	358	377	123	102	275	0	439
	2000	CS	0	303	448	213	74	216	12	408
		CS	180	303	448	116	82	224	16	509
		SNS	0	206	448	206	93	143	0	397
		SNS	180	206	448	117	94	123	0	508
	2001	SNS	0	561	297	175	97	368	13	425
		SNS	180	505	297	104	103	314	15	502
		RF	0	36	297	150	109	-98	20	410
		RF	180	70	297	105	112	-96	21	492
		FI	0	72	297	152	111	-49	17	394
		FI	180	107	297	104	115	-49	20	483
	2002	SNS	0	1238	365	212	134	1214	50	361
		SNS	180	1194	368	152	128	1155	56	439
		FI-30[b]	0	512	365	180	89	500	60	344
		FI-30	180	502	368	138	92	438	58	445
		FI-50	0	467	365	193	128	535	57	288
		FI-50	180	472	368	138	128	475	65	420
Los Baños	2002	CS	0	925	85	276	42	469	8	316
		CS	150	885	50	163	58	451	6	385
		FI	0	690	85	144	56	408	23	303
		FI	150	655	50	89	73	329	20	380
	2003	CS	0	1021	92	261	49	557	4	348
		CS	150	1021	85	153	42	574	1	422
		FI	0	715	92	182	61	396	16	307
		FI	150	715	92	142	60	369	16	372

[a] CS=continuously submerged RF=rainfed
SNS=alternately submerged-nonsubmerged FI=flush irrigation
[b] FI-30=flush irrigation with threshold in soil water tension of 30 kPa (see Chapter 3).

Table 7. Simulated effect of water regime, soil permeability, and groundwater table depth on components of the water balance (mm) at (A) Tuanlin and (B) Los Baños.

(A) Tualin

Water regime[a]	Evaporation				Transpiration				Net percolation			
	impermeable[b]		permeable		impermeable		permeable		impermeable		permeable	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Groundwater table depth at 20-cm												
CS	135	15	135	15	487	47	487	47	518	62	1719	64
SNS	121	11	97	10	483	48	481	46	394	64	1205	67
RF	97	13	63	12	480	48	478	46	–32	149	4	151
FI	100	15	72	13	466	48	443	46	–22	148	30	148
Groundwater table depth at 60-cm												
CS	137	17	141	17	486	48	482	47	517	62	1709	82
SNS	124	13	103	10	478	47	472	45	362	74	1050	79
RF	101	14	67	12	455	36	448	33	–11	135	29	139
FI	117	15	93	14	435	53	379	46	112	115	261	121
Groundwater table depth at 100-cm												
CS	137	17	141	18	486	48	482	47	517	62	1709	82
SNS	126	13	104	11	476	48	470	46	362	74	1050	79
RF	106	12	72	12	431	36	419	35	7	121	54	126
FI	128	13	116	14	422	57	310	49	149	94	341	100

(B) Los Baños

Water regime	Evaporation				Transpiration				Percolation			
	impermeable		permeable		impermeable		permeable		impermeable		permeable	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Groundwater table depth at 20-cm												
CS	160	8	159	8	422	39	421	39	471	31	1629	40
SNS	139	11	121	10	418	39	416	39	300	33	1153	57
RF	57	15	41	10	406	37	406	37	–294	118	–278	122
FI	50	15	37	10	419	39	417	39	–310	121	–296	124
Groundwater table depth at 60-cm												
CS	160	8	159	8	422	39	421	39	471	31	1624	38
SNS	141	10	119	10	414	39	410	39	267	43	919	46
RF	59	15	42	10	327	15	345	12	–217	82	–218	94
FI	76	11	61	7	411	38	405	38	–59	54	149	45
Groundwater table depth at 100-cm												
CS	160	8	159	8	422	39	421	39	471	31	1624	38
SNS	140	10	119	10	413	38	408	39	259	41	913	42
RF	64	15	47	10	264	38	274	32	–159	62	–152	70
FI	82	11	59	9	379	27	378	34	–19	47	221	51

[a] CS=continuously submerged   RF=rainfed
SNS=alternately submerged-nonsubmerged   FI=flush irrigation

[b] ‘less permeable’ stands for a fixed percolation rate of 4.0 mm d^{-1} and a saturated hydraulic conductivity of 3 mm d^{-1} in the layer between 10-15 depth and was set as the most impermeable layer; ‘more permeable’ has fixed percolation rate of 14.0 mm d^{-1} and a saturated hydraulic conductivity of 30 mm d^{-1} in the 10-15 cm layer.

The amount of evaporation ranged between 41 and 160 mm and was highest for CS, followed by SNS. In these treatments, evaporation was higher at Los Baños than at Tuanlin because of more leaf area development at Tuanlin (data not shown). The evaporation in the FI and RF regimes was dependent on rainfall, and was higher at Tuanlin (more rainfall) than at Los Baños. The highest reduction in evaporation between a water-saving treatment and CS was 38 mm at Tuanlin and 110 mm at Los Baños.

Under CS regimes, the amount of transpiration was some 65 mm higher at Tuanlin than at Los Baños because of more leaf area development at Tuanlin. The transpiration sum was smaller in the water-saving regimes than in the CS regimes. The highest reduction in transpiration between a water-saving treatment and CS was 64 mm at Tuanlin and 158 mm at Los Baños.

The amounts of irrigation and percolation were closely correlated. The amounts of irrigation and percolation were both highest for CS followed by SNS and FI. The amounts of irrigation and percolation were highly dependent on the soil permeability. At Tuanlin, the amount of irrigation water needed to maintain continuous submergence was 1860 mm in the permeable soil, and 720 mm in the impermeable soil. At Los Baños, these amounts were 2040 mm and 900 mm, respectively. In the permeable soil, the percolation losses in the CS regimes were 87% of the total amount of irrigation water input at Tuanlin and 77% at Los Baños. These high losses were reduced in the water-saving regimes. For example, at Tuanlin, the SNS regime saved some 600 mm compared with CS in the permeable soil and about 300 mm in the impermeable soil. At Los Baños, water savings with SNS reached around 800 mm in the permeable soil and 240 mm in the impermeable soil.

Table 8 presents the simulated irrigation requirements and yields obtained. At both locations, yields with SNS regimes were within 96% of the yield that can be attained with CS at any groundwater table depth for both soil types. The yield response to RF and FI regimes depended on soil permeability, groundwater table depth, and rainfall. Especially the yield in the RF regime dropped significantly with increasing groundwater table depth. Also, the yield variation between years increased with groundwater table depth. These effects were more pronounced in the permeable soil than in the impermeable soil, and more pronounced at Tuanlin than at Los Baños.

The effect of weather can be deducted from the standard deviations of the water balance components and yield. Year-to-year variation in rice yield was high (up to 1600 kg ha^{-1}) under RF conditions when groundwater table depth was 100 cm deep. When the groundwater table was only 20 cm deep, the year-to-year variation in yield was nearly the same as for the other water regimes. The year-to-year variation in evaporation was less than 20 mm at both sites. A larger variation was observed for

Table 8. Simulated effect of water regime, soil permeability, and groundwater table depth on irrigation requirements (mm) and associated yield (kg ha^{-1}) at (A) Tuanlin and (B) Los Baños.

(A) Tuanlin

Water regime[a]	Irrigation				Yield			
	impermeable[b]		permeable		impermeable		permeable	
	mean	SD	mean	SD	mean	SD	mean	SD
Groundwater table depth at 20-cm								
CS	596	123	1796	174	8618	379	8618	379
SNS	454	107	1239	140	8591	380	8578	373
RF	NA	NA	NA	NA	8501	405	8472	392
FI	0	0	0	0	8339	399	8019	398
Groundwater table depth at 60-cm								
CS	596	123	1787	167	8539	378	8376	379
SNS	420	105	1080	129	8394	366	8330	377
RF	NA	NA	NA	NA	7800	525	7596	651
FI	120	53	189	91	7576	533	6321	530
Groundwater table depth at 100-cm								
CS	596	123	1787	167	8539	378	8374	379
SNS	420	105	1080	129	8314	373	8268	383
RF	NA	NA	NA	NA	6751	1086	6281	1191
FI	154	61	223	89	6962	727	4413	698

(B) Los Baños

Water regime	Irrigation				Yield			
	impermeable		permeable		impermeable		permeable	
	mean	SD	mean	SD	mean	SD	mean	SD
Groundwater table depth at 20-cm								
CS	883	132	2040	145	7634	183	7634	183
SNS	689	115	1522	171	7627	186	7630	188
RF	NA	NA	NA	NA	7372	202	7374	202
FI	0	0	0	0	7670	170	7656	179
Groundwater table depth at 60-cm								
CS	883	132	2035	140	7634	183	7634	183
SNS	653	106	1279	160	7589	200	7570	216
RF	NA	NA	NA	NA	5598	931	6033	756
FI	269	92	456	111	7565	192	7491	209
Groundwater table depth at 100-cm								
CS	883	132	2035	140	7634	183	7634	183
SNS	643	113	1272	155	7576	201	7553	223
RF	NA	NA	NA	NA	3521	1639	3684	1605
FI	283	87	499	125	6785	205	7003	185

[a] CS=continuously submerged; RF=rainfed; SNS=alternately submerged-nonsubmerged; FI=flush irrigation

[b] 'less permeable' stands for a fixed percolation rate of 4.0 mm d^{-1} and a saturated hydraulic conductivity of 3 mm d^{-1} in the layer between 10-15 depth and was set as the most impermeable layer; 'more permeable' has fixed percolation rate of 14.0 mm d^{-1} and a saturated hydraulic conductivity of 30 mm d^{-1} in the 10-15 cm layer.

transpiration, which could go up to 50 mm. The year-to-year variation in percolation was higher for RF and FI than for CS and SNS regimes because the RF and FI regimes largely depended on rainfall as water input.

Discussion

This study used the ORYZA2000 simulation model to support the analysis of the water balance of field experiments on water-saving irrigation technologies, and to extrapolate the experimental results to different hydrological conditions (groundwater table depth, soil hydrological properties) and years. ORYZA2000 was first evaluated for its simulation of crop growth and soil water balance variables. Based on a satisfactory simulation of leaf area index, biomass, yield, field water level, and soil water tension, the components of the water balance namely evaporation, transpiration, percolation, capillary rise, and change in field water storage were calculated for the field experiments. In the subsequent exploration of water-saving technologies, we concentrated on simulated yield, irrigation requirement, evaporation, transpiration and net percolation.

If only evaporation is considered as a 'real' water loss on field scale, such as suggested by Seckler (1996), limited amounts of water can be saved through the tested water-saving irrigation regimes compared with continuous submergence. The largest savings in evaporation were obtained with flush irrigated rice, and were at maximum 38 mm at Tuanlin and 110 mm at Los Baños. However, relatively large evaporation savings can be accompanied by considerable yield losses, especially when the groundwater table is relatively deep. To reduce evaporative losses, adequate N fertilization is at least as important as the water regime, as was shown in the water balances of the field experiments (Table 6).

At the field level, percolation flows are real water losses for individual farmers. If water is scarce or costly at the field level, such as in pump-irrigation schemes, any unproductive water flowing out of a farmers' field should be minimized. Soil type is a major factor affecting percolation, and a combination of continuous submergence on permeable soils leads to high percolation rates. On permeable soils, SNS can save large amounts of water by reducing percolation, while at the same time maintaining high yield levels. In the SNS regimes of our simulation study, severe water stress to the crop was avoided by re-irrigating the crop when the soil water tension in the root zone increased to only 0.5 kPa. In practice, this threshold may be exceeded, and yield reduction may occur. Belder et al. (2004) and Li (2001) reported water savings without yield loss under SNS regimes, whereas Mishra et al. (1990), Singh et al. (2001) and Tabbal et al. (2002) reported (small) yield reductions under SNS regimes. Bouman and Tuong (2001) pointed out the danger that SNS regimes could even lead to enhanced water use (over continuous submergence) due to severe shrinking and the formation of cracks that promote rapid vertical water movement. Higher water use in SNS than under continuous submergence was reported by Lu et al. (2000) because of the development of cracks in the plough layer during the drying periods in between the flooded conditions. In the analysis of our field experiments, we found higher percolation rates of the ponded water layer in SNS than under continuous submergence at Tuanlin (Table 3), although the seasonal percolation was still lower under SNS than under continuous submergence because of the absence of percolation during the nonsubmerged days. Wopereis et al. (1994) reported that percolation rates and the saturated conductivity changed in the course of a growing season, which he ascribed to trampling of the plow pan at times of manual weed control. Although the soil water balance model PADDY can handle changes in percolation rate from the ponded water layer during the growing season, simulations could be further improved by allowing changing values for saturated conductivity (and other Van Genuchten parameters) as well.

At Los Baños, the FI regime with a groundwater table depth of 60- and 100-cm benefited from non-puddling resulting in a yield that was still 99% and 90% of the attainable yield under CS regimes, respectively. Non-puddling for the Tuanlin soil, resulted in faster downward movement of rainfall and FI yields were reduced by 19% at 60 cm groundwater and 34% at 100 cm groundwater table depth averaged over the soil types. The dry land preparation thus increased hydraulic conductivity of the layer that had previously been the plough pan. In water scarce situations, the increased K_{sat} made FI a better strategy at Los Baños and RF with puddling a better strategy at Tuanlin. On lighter textured soils, puddling intensity significantly reduces K_{sat} of the plough layer thereby reducing percolation (Singh et al., 2001; Kukal and Aggarwal, 2002).

A deeper groundwater table depth – reflecting a possible situation when water-saving regimes are adopted on a large scale – did not result in higher percolation and irrigation water requirements for CS and SNS regimes compared with a shallow groundwater table depth of 20 cm. On the contrary, irrigation water requirements in SNS regimes were slightly higher when the groundwater table depth was 20 cm compared to 60- and 100-cm. The explanation for this is that these regimes used puddling, and downward water flow was governed by the K_{sat} of the plough layer. Groundwater at 20-cm increased water flux at 20-cm because the soil below 20-cm was saturated, and the soil water conductivity is higher under saturated than under nonsaturated conditions.

Mishra et al. (1990) observed an increased irrigation water requirement with deeper groundwater table depths and formulated recommendations for SNS regimes based on the groundwater table depth. According to them, the periods of nonsubmergence should be shorter (1–3 days) when groundwater table depth fluctuates between 13 and 126 cm and can be extended to 5 days when the groundwater table depth fluctuates between 1 and 92 cm. The reason for the different response compared to our analysis is that in their experiments, the K_{sat} values of the puddled layer were probably higher due to a lighter soil texture. The groundwater table depth highly influenced water use and yield under RF and FI regimes, whereas soil type highly influenced irrigation water requirements for CS and SNS regimes.

In one-dimensional water balance models such as PADDY, the groundwater table is usually a user-defined external boundary condition. There is no feed back between water fluxes in the soil profile and groundwater table depth. In reality, the groundwater table depth can respond quickly to rainfall or irrigation events, such as reported by Bouman et al. (2005) for our field experiments in Los Baños. Moreover, the groundwater table underneath a specific field is also influenced by the hydrology of the wider environment, as was found in the rainfed and flush irrigated fields in Tuanlin. To improve the model for making predictions of what would happen to hydrological conditions, water savings, and yield, when farmers introduce water-saving technologies, a coupling of crop growth simulation models with three-dimensional, regional hydrological models is needed.

This study indicates that under high rainfall conditions, irrigation water savings can be made by applying SNS or, when groundwater tables are shallow, at the same time, by growing purely rainfed rice. At Tuanlin, with 20-cm deep groundwater tables, rainfed rice yields were the same as irrigated rice yields with continuous submergence. Even with a groundwater table down to 60 cm, simulated rainfed yields were still about 87% of the fully irrigated yield. Aerobic rice with flush irrigation is a promising option for the dry season at Los Baños if water is really scarce. With groundwater tables at 60 and 100 cm depth, simulated rice yields with flush irrigation were still about 90% of the CS yields with when plots were re-irrigated when the soil water tension in the root zone reached 50 kPa thereby requiring only up to 420 mm of irrigation water. The reduced apparent N recovery in flush irrigation in Chapter 4 was not taken into account in the scenario study which led to higher simulated yields in this regime.

This study helped in identifying most suitable water (saving) regimes given the soil type, weather conditions, and predominant groundwater table depth. Other factors that influence this decision making by farmers are of socio-economic nature, such as relative scarcity of water, price of water and rice, demand for rice, government policies, etc, but lie outside the scope of this research.

Acknowledgements

We wish to thank ACIAR, which funded the experiments at Tuanlin under ACIAR project LWR1/2000/030, and the staff of Tuanlin station for their assistance in carrying out the experiments. We are also grateful to the S. Peng, R.V. Visperas, and A.R. Castañeda who were responsible for data collection at Los Baños. This research contributes to the Comprehensive Assessment of Water Management in Agriculture, supported by a grant from the Dutch Government of the Comprehensive Assessment of Water Management in Agriculture.

CHAPTER 6

General discussion

Two main strategies to grow more rice with less irrigation water were identified. The first strategy is to save water while maintaining a high yield thus enhancing water productivity; the second one is to boost yields under optimal irrigation conditions, which also enhances water productivity. The first strategy focuses on irrigation water management and soil hydrology, and the second strategy focuses on other production factors besides water management, like nitrogen fertilization.

Effects of water regime on crop growth and grain yield

The results confirm findings of other authors (Wu, 1999; Li and Barker, 2004; Pirmoradian et al., 2004; Shi and Hengsdijk, 2001; Singh et al., 1996) that irrigation water can be saved without causing yield reduction and continuously submerged conditions are not needed for optimal growth of rice. Under continuously submerged conditions grain yield was 8.1–9.2 t ha^{-1} at Tuanlin with a hybrid cultivar and 180 kg N ha^{-1}, 7.2 t ha^{-1} at Muñoz with IR72 and 180 kg N ha^{-1}, and 6.8–7.3 t ha^{-1} at Los Baños with the improved upland cultivar Apo and 150 kg N ha^{-1}. Yield under submerged-nonsubmerged (SNS) conditions in the same years, were statistically the same at Tuanlin and Muñoz. At Los Baños, the aerobic flush irrigation regime resulted in 15–39% lower yields than under continuous submergence. Other water-saving regimes that were tested at Tuanlin (partially rainfed, flush irrigation, raised beds) resulted in lower yields than under SNS but only the latter regime was significantly different. Within seasons, yields in 0-N plots were the same under all kinds of water regimes, indicating that the soil N supply and uptake remained largely unaffected by water regimes. Water stress was thus more pronounced at higher input levels of N which was also found by Aragon and De Datta (1982).

Other water-saving regimes that were not part of this thesis are direct (dry) seeding, sprinkler irrigation which was mostly tested in the USA (McCauley, 1990; Westcott and Vines, 1986) and the groundcover rice production system tested in China (Lin et al., 2002). In the latter system the soil is covered with plastic to reduce evaporation, and it is also used to increase soil temperature.

Increasing internal drainage in combination with deficit irrigation in 2002 at Tuanlin, led to reduced yields in all water regimes. Soil water tension in the root zone went up to 30–50 kPa, thereby causing stress for the rice plants. Rice is very sensitive to soil water status; even soil water tensions of 10 kPa already reduced leaf expansion.

This response of rice to soil water status highlights the risk that is involved in adopting water-saving strategies.

Improvement of water productivity

Water productivity, as was shown in the introductory part of this thesis, can be expressed as WP_{ET} and WP_{I+R} and both have a different focus.

Turner (1997) suggested two ways to enhance water productivity under water-short conditions: (1) plant genetic improvement and (2) agronomic practices. Tuong (1999) argued that improving water productivity involves (1) increasing yield per unit of ET and (2) reducing the portion of water input to the field that is not available for crop ET and thereby implicitly focused on WP_{ET} for the first and WP_{I+R} for the second approach. Four approaches to improve water productivity are discussed here below; some refer to WP_{ET} and others refer to WP_{I+R}.

Water management

Water-saving regimes proved to reduce evaporation and to improve WP_{ET} but the increase was generally small (Chapter 3), which was also found by Dong et al (2001). Most water-saving practices are intended to reduce water use on field scale and improvement will be expressed more by WP_{I+R} than by WP_{ET}. Significant improvements on WP_{I+R} were possible in SNS compared to CS, but WP_{I+R} was not always higher for the water-saving regimes as was shown in Chapter 4 for the aerobic flush irrigated treatment.

Tuong (1999) and Tuong and Bouman (2003) listed the following water management practices to increase WP_{I+R}:

- Provision of tertiary infrastructure, such that irrigation water supply reaches individual farmers;
- Proper weed management to reduce transpiration through weeds and reduce competition for nutrients and light with the rice crop;
- Land leveling to improve an equal distribution of water;
- Minimizing idle periods during land preparation to reduce evaporation;
- Minimizing downward percolation through puddling and reducing the water head;
- Direct (dry) seeding instead of transplanting;
- Changing of crop schedule to maximize light interception and reduce ET.

Furthermore, soil tillage after the last harvest reduced bypass flow of water through cracks when the fields were inundated for land preparation (Cabangon and Tuong, 2000).

Some of these practices are difficult for farmers to implement because of insecurity about irrigation water availability or socio-economic constraints such as labour.

Implementation of water-saving regimes by farmers heavily depends on reliability of irrigation water supply. According to De Wit (1992), societies should be willing to invest in improving water management to optimize yields, because when water is in optimal supply, it's relatively more costly than when water is in abundance.

N management

WP_{I+R} and WP_{ET} were both enhanced by N fertilization, because yields increased, whereas ET only slightly increased under fertilized conditions and irrigation + rainfall were similar in fertilized and unfertilized plots. The improvement of WP_{ET} with N fertilization had two main reasons: (1) a reduction of evaporation and (2) a higher transpiration use efficiency (TUE), where TUE is the amount of biomass (or yield) divided by the amount of transpiration. A reduced evaporation is the direct consequence of enhanced leaf growth. The reduction of evaporation under better N fertilization and subsequent higher WP_{ET} was also described for wheat by Turner et al. (1987) and by Ehlers and Goss (2003). Higher TUE is due to the linear relationship between leaf N content and assimilation rate under saturated light (Peng et al., 1995). TUE for Los Baños and Tuanlin for several categories of water regimes, soil N supply, and fertilizer-N levels are presented in Figure 1. TUE increased with fertilizer

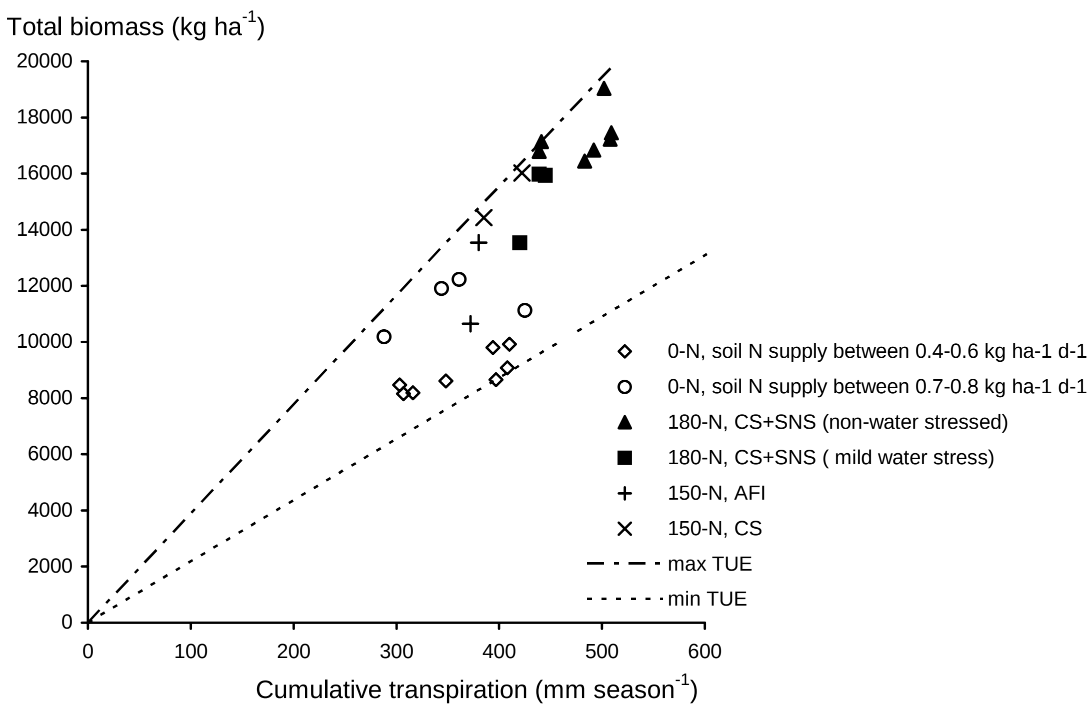

Figure 1. Transpiration use efficiency (biomass/transpiration) at Tuanlin and Los Baños as affected by water regime, fertilizer N supply, and soil N supply with minimum and maximum values accentuated by lines.

application, increased level of soil N supply, and absence of water stress, in this order of importance. Minimum and maximum TUE are represented by dashed lines and is 3.9 kg m^{-3} and 2.2 kg m^{-3}, respectively. The reciprocal is often used as the water requirement. This water requirement is often quoted at 1000 L kg^{-1} grain (Setter et al., 1995; Tuong, 1999). If we assume a harvest index of 0.5, we find minimum and maximum values of 514 L kg^{-1} and 916 L kg^{-1} and thus the 1000 L kg^{-1} represents poorly fertilized conditions.

The strong N effect on growth, yield and biomass underpin the importance of N management. Fertilizer N is commonly available and used, but timing and dosage often mismatch crop demand (Cassman et al., 1998). Moreover, N losses pose a threat to the environment. New techniques such as the leaf color chart and chlorophyll meters (Peng et al., 1996; Balasubramanian et al., 1999) are increasingly used to improve crop growth and reduce hazardous N losses. Soil N supply turned out to be variable between sites and years which was also observed by Cassman et al. (1996). Monitoring of indigenous N resources – and in general using the intrinsic capacity of wetland rice systems to conserve N – provide further opportunities for an increase in N efficiency (Cassman et al., 1998).

Genotype

Plant physiological response to water deficit is dependent on the genotype. Germplasm development to increase harvest index and yield and to reduce duration of the crop cycle resulted in a threefold increase in WP_{ET} compared to traditional cultivars (Tuong and Bouman, 2003). The genetic variation in transpiration:assimilation ratios indicates that there is scope for further improvement (Peng et al., 1998; Kondo et al., 2004). Further improvements in plant-water relationships through molecular and genetic methods are soon to be expected (Bennett, 2003). Changing the rice crop from a C_3 to a C_4 pathway is yet another approach to improve plant-water relationships that is currently be undertaken (Sheehy and Mitchell, 2001).

In this thesis there was no real comparison of genotypes, since at the three sites, three different cultivars were used. At Tuanlin and Muñoz, locally high-yielding cultivars were used, whereas at Los Baños an improved upland cultivar was used. This was because the purpose of the experiment at Los Baños was different from the other two sites. At Los Baños the sustainability and management of the aerobic rice system was the objective, whereas at Tuanlin and Muñoz the experiments aimed at saving irrigation water while maintaining high yields.

Ying et al. (1998) compared high yielding hybrid and inbred cultivars in Yunnan, China and Los Baños, Philippines. They reported that the Chinese F1 *indica* hybrid cultivar Shanyou 63 had a higher grain yield at both locations than the *indica* inbred

IR72, but largest differences were between locations. Biomass of Shanyou 63 was almost the same as for IR72 in the Philippines but was much higher in China, indicating that improved crop growth of the hybrid was better expressed under subtropical conditions than under tropical conditions. Higher biomass and yield of hybrids compared to inbred cultivars was also found by Yang et al. (1999) in China, who suggested that this difference was because of higher N uptake, higher LAI after anthesis, and greater remobilization of N. Under subtropical conditions, therefore, hybrid cultivars show a higher WP_{ET} than inbred cultivars.

Other agronomic practices

The difference between attainable and actual yield is called ‘yield gap’. Yield gaps in rice still widely occur throughout Asia. Dobermann and Cassman (2002) estimated that current rice yields are within 40–65% of attainable yields and nutrient management is the key to improve this situation. Modern farmers usually obtain higher yields, suggesting that there is also a knowledge gap (Tran, 2001). According to Tran (2001) the narrowing of the yield gap requires an integrated approach and includes deployment of new proven technologies for production, understanding of farmers’ actual constraints to high yield, policy interventions, and adequate institutional support to farmers. Through raising yields, both WP_{ET} and WP_{I+R} will substantially be increased. Tuong (1999) and Tuong and Bouman (2003) also listed soil fertility management as an important strategy to improve WP_{ET} and WP_{I+R}.

In his review of resource use efficiency, De Wit (1992) argued that most production factors are used more efficiently with increasing yield level, due to further optimization of growing conditions.

Effects of water regimes on N losses and apparent N recovery

N losses

N uptake and recovery in non water-stressed SNS treatments were similar to CS regimes despite short periods of soil aeration. Uptake under aerobic flush irrigated conditions was lower because of a reduced crop N-demand whereas soil N transformations may have promoted faster nitrification-denitrification. Soil sampling under SNS and aerobic conditions indicated more NO_3 formation and less extractable NH_4 when soils were (temporarily) aerobic (data not presented). The N form can be important in uptake processes as the rice crop prefers a mixture of NO_3 and NH_4 above the single form (Qian et al., 2004). Soil aeration can therefore be beneficial for crop growth. On the other hand, NO_3 is prone to denitrification upon re-irrigation (Reddy and Patrick, 1975) and possibly to leaching (see next section).

Statistical analysis of crop parameters showed that water × N interactions were mostly absent, which could be ascribed to the experimental set up at Tuanlin and Los Baños of using only a zero and a 'full' N dosage. Under non-water stressed conditions, such as for SNS in Muñoz and for SNS in Tuanlin 1999-2001, N × water interaction was absent. Under water-stressed conditions such as at Tuanlin 2002 and for aerobic flush-irrigated rice at Los Baños, the soil water status limited plant growth, thereby setting a maximum limit to crop N demand.

Environmental impact

The higher occurrence of NO_3 in aerobic soil compared to NH_4 poses the question of NO_3 leaching. This question was also dealt with in Chapter 4 where CS and AFI regimes were compared regarding NO_3 leaching. For the conditions of this experiment – clay soil and soil water content close to saturation – NO_3 leaching hardly occurred and was not significantly higher in the flush irrigated treatment in aerobic soil than under CS in permanent anaerobic soil. On lighter textured soils, NO_3 leaching poses a higher risk (Pirmoradian et al., 2004; Keeney and Sahrawat, 1986). Groundwater is still often used for drinking water (Bouman et al., 2002).

Field experiments have shown a significant effect of water regime on the greenhouse gas emissions of methane (CH_4) and nitrous oxide (N_2O). Increased soil aeration decreased CH_4 emissions but increased N_2O emissions (Corton et al., 2000; Cai et al., 1997; Xu et al., 2004; Bronson et al., 1997). Fertilizer N source and amount influenced the emission levels of both CH_4 and N_2O (Cai et al., 1997). Currently, researchers are defining the optimal range of redox potentials to reduce the emissions of both CH_4 and N_2O in rice soils (Sarah Johnson, pers. comm.).

Water balance components; options for water saving on the field scale

The field experiments revealed the strong influence of the groundwater table depth in water availability for the crop. At Tuanlin and Muñoz, groundwater table depths for irrigated lowland rice were within 35 cm below field level in continuously submerged and adjacent alternately submerged-nonsubmerged plots.

The field experiment at Los Baños, where aerobic flush irrigated rice was compared with continuously submerged rice, revealed that groundwater table depth depends on the water regime. The groundwater table depth under continuous submergence was still near the field level during the growing season, whereas groundwater table depth under flush irrigation reached depths of 110–160 cm. The observations on groundwater table depth led to the explorative study in Chapter 5, in which four water regimes were compared regarding water balance components and yield for two types of soil permeability and three different groundwater table depths.

The water balance computations revealed that ET ranged between 447 and 625 mm. Irrigation water in excess to ET is mostly lost though percolation, because difference in storage and capillary rise were of minor importance in the water balance (Figure 2). The two dashed lines represent minimum and maximum ET as found in rice by Zwart and Bastiaanssen (2004). In theory, the crop can be supplied with irrigation water to just satisfy the ET requirement which ranges between 300 and 900 mm season^{-1}. In conditions with relatively impermeable soils and shallow groundwater tables, the ideal situation might be attainable. In practice, however, P will occur on most soils especially if the field is frequently submerged. Field submergence is often practiced by farmers as 'insurance irrigation'. A more efficient delivery by canal operators and better communication between operators and farmers may lead to a reduced distrust, less 'insurance irrigation' and less P. Whether reducing P leads to 'true' or 'paper' savings (Seckler, 1996) lies outside the scope of this thesis.

Water-saving regimes can play a role in optimizing water use on the field and regional scale. The choice of best practice in water-saving regimes should be based on biophysical factors such as described in this thesis – groundwater table depth, weather, soil type, and cultivar – that are constrained by socio-economic factors such as labour, price of water, price of rice grain, which are outside the scope of this thesis.

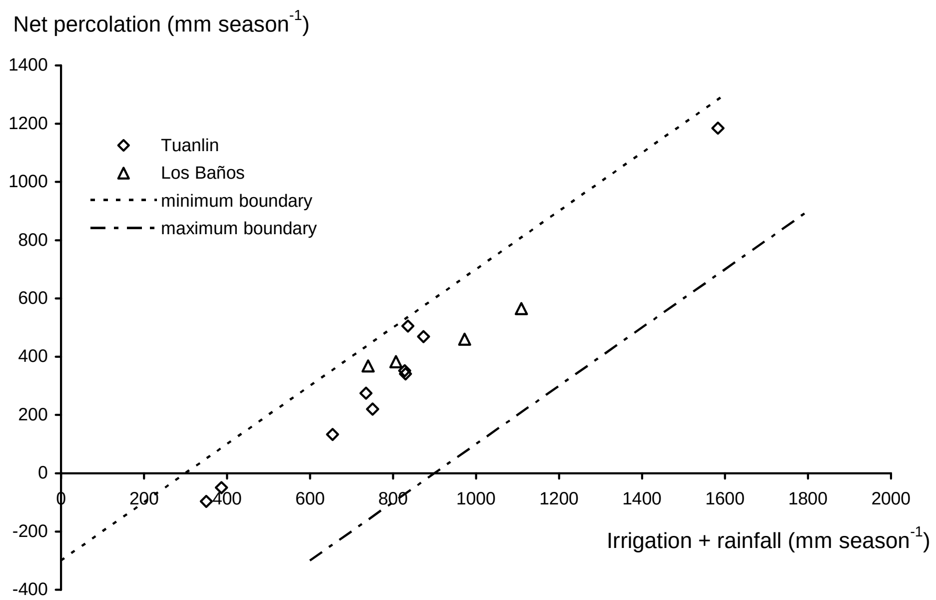

Figure 2. Relationship between irrigation + rainfall and net percolation for Tuanlin and Los Baños. The minimum and maximum boundaries are calculated using minimum and maximum observed ET in rice from a large data set (Zwart and Bastiaanssen, 2004).

Evaluation of water saving options with the crop growth model ORYZA2000

The crop growth model ORYZA2000 was used for simulating biomass and grain yield and calculating the components of the water balance. The mechanistic crop and soil model was extensively evaluated under irrigated (Bouman and Van Laar, 2005) and rainfed conditions (Boling et al 2005). The performance under water-saving regimes turned out to be satisfactory, because good matches between observed and simulated crop and soil water balance parameters were found. The advantages of using this model are many such as:

- Effect of weather on crop development, growth and yield could be accurately simulated;
- Experimental results could be generalized and so cross location comparisons could be made;
- Cost of more field experiments could be reduced.

Disadvantages of using ORYZA2000 are the large data set that is required to calibrate/validate the model. So far, ORYZA2000 was used for scientific purpose and not for extension or use by farmers for tactical decision making. Model improvement is suggested for simulation of the sink size in hybrid cultivars and leaf area development under conditions of low N supply. Well-calibrated and validated models are needed to study prospects for water saving on regional scale and these models should ideally require only few input data (Singh, 2005).

Conclusions and recommendations

The following conclusions are derived from the experimental and modelling study to improve water productivity and save water in lowland rice production systems:

- Hydrological parameters such as groundwater table depth and soil permeability are more important for the amount of water that can be saved than the different modifications of the water saving regimes. Under experimental conditions of low soil permeability and a shallow groundwater table, submerged-nonsubmerged regimes saved 15–18% of irrigation water as compared to continuous submergence without yield reduction. Modelling studies showed that higher savings are possible in more permeable soils when irrigation is fine-tuned with crop demand thereby avoiding water stress during critical growth stages.
- Among the water-saving regimes, a submerged-nonsubmerged regime turned out to be the most stable for maintaining a high yield; the modelling study showed that irrigation requirements in submerged-nonsubmerged conditions are about half of that of continuous submergence with a more permeable and a less permeable soil type. The savings are mostly on percolation and evaporation is also reduced.

- N management plays a key role to produce more rice with less water. N supply promotes leaf area growth, biomass growth, grain number and yield per unit area and reduces evaporative losses. As a result WP increased dramatically when water was not limiting.
- Water-saving regimes resulting in aerobic soil conditions changes soil-N transformation processes. When the regime leads also to crop water deficit, crop growth will be reduced and as a consequence N uptake will be less. Under such conditions, apparent N recovery will be reduced and more N is lost to the environment (atmosphere, groundwater)
- Optimum water-saving regimes depend on relative (economic) and absolute (physical) water scarcity. In the first case current irrigation practices should be improved by fine-tuning the dose and timing of irrigation to the requirements of a high-yielding crop. In the latter case a transition to aerobic rice systems can save 40% or more in water input with a yield reduction of 20–25%.

In general, time and site-specific water management requires a detailed knowledge on crop growth and development, soil hydrological processes, and N cycling in the soil-plant system.

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Summary

In Asia, rice is the predominant staple food. Demand for rice is expected to increase with 10–20% for the coming 20 years, taking into account population growth and a change in diet. The increase in rice production has to come from higher yield per unit of land because land area under rice is declining. Urbanization and economic growth cause a rapid decrease of water availability for irrigated agriculture. Rice farmers in water scarce regions who depend on irrigation, are increasingly facing water shortages during the cropping season.

One option to deal with a reduced irrigation water supply is the adoption of water-saving regimes on field scale. Traditionally, rice farmers tend to keep their fields continuously submerged (CS) to be assured of ample water supply to the drought-sensitive rice crop and to control weeds. In water-saving regimes farmers allow the soil to dry for periods of several days resulting in alternate submergence-nonsubmergence (SNS). Crop responses to SNS in terms of amount of water saved and effects on yield are reported to be variable.

More recently, a system called 'aerobic rice' was developed by researchers from IRRI and China for regions with a high frequency of water scarcity. In this system, soils are 'nonpuddled' and 'nonsaturated' such that rice is grown like an upland crop. The difference with the upland rice ecosystem is the use of supplementary irrigation, of higher yielding cultivars, and of other inputs such as fertilisers and biocides. Aerobic rice systems aim at relatively high and stable yields using only around 50% of the water used in CS. So, water saving is high compared to CS conditions but at the expense of a yield penalty.

Nitrogen (N) is the most important nutrient in rice production and limits crop growth and yield in almost all environments. Under CS conditions, N is almost solely available as ammonium whereas in SNS and aerobic systems soil aeration will enhance nitrification. Altered N transformation may lead to higher N losses, reduced N availability, and may constrain crop growth and yield.

Water productivity (WP), calculated as grain yield per unit water use (kg m^{-3}) was applied to evaluate the effect of water regime and N level on water use efficiency and crop productivity. Water use is expressed as evapotranspiration (ET) or irrigation + rainfall (I+R).

The main goal of this thesis was to quantify the effects of water-saving regimes on water productivity, N-use efficiency, and yield by a combined experimental and modelling approach. The study also investigated the role of subsurface hydrology in assessing the effects of water-saving regimes on the water balance. Finally the

simulation model ORYZA2000 was used to calculate water balances for various water (saving) regimes. The model was also used to gain insight in how water-saving regimes would affect water use and yield under future scenarios of deeper groundwater table depths and how weather and soil permeability would affect these relationships.

Effects of water regimes and levels of N application were studied at three sites: Tuanlin in Hubei province in China, Muñoz in central-Luzon in the Philippines, and Los Baños in the Philippines. Tuanlin and Muñoz are located within irrigation systems where spatial and temporal water shortages occur. Levels of N application were 0 and 180 kg ha^{-1} at Tuanlin, 0, 90, and 180 kg ha^{-1} at Muñoz, and 0 and 150 kg ha^{-1} at Los Baños. The cultivars used in the experiments were the hybrids 2You501 and 2You725 at Tuanlin, the inbred cultivar IR72 at Muñoz, and the improved upland cultivar 'Apo' at Los Baños.

Grain yields under SNS were not lower than under CS at Tuanlin and Muñoz thereby using 15−18% less irrigation water resulting in a significantly higher WP_{I+R} in two out of three seasons. The (perched) groundwater tables in the same fields were less than 35 cm during the growing season and at Muñoz the soil water potential at 15 cm under SNS never went below than −10 kPa so that water deficit hardly occurred in these trials. In a different season at Tuanlin when the groundwater was lowered thereby increasing internal drainage, biomass, grain yield, and N uptake were all reduced. An analysis of the data of three seasons at Tuanlin showed that biomass and apparent N recovery declined linearly with the duration of nonsubmergence of fields.

In all seasons with a shallow groundwater table at Tuanlin, N application significantly increased grain yield largely through an increased biomass and to it related grain number. Under conditions of no or limited water stress, yields were 4.1–5.0 t ha^{-1} and 6.8–9.5 t ha^{-1} with 0 and 180 kg N ha^{-1}, respectively. Yields were higher at Tuanlin than at Muñoz due to a longer growing season and the use of a hybrid cultivar. If only mild water stress occurred, WP_{ET} was significantly increased by N application and ranged from 0.70 to 1.17 kg m^{-3} and from 1.27 to 1.66 kg m^{-3} in 0-N plots and with 180 kg N ha^{-1}, respectively. Water-saving regimes also increased WP_{ET} under non water-stressed conditions compared with CS due to a reduced evaporation.

Aerobic rice was compared with CS conditions at Los Baños. The aerobic fields were flush irrigated when the soil water potential at 15-cm depth reached –30 kPa. The yield under aerobic conditions with 150 kg N ha^{-1} was on average 5.3 t ha^{-1}, 27% lower than under CS. Irrigation water use in aerobic rice was 39% lower than under CS thus leading to a higher WP_{I+R}. N content of leaves at 150 kg N ha^{-1} was nearly the same for aerobic rice and CS conditions, indicating that crop growth under aerobic conditions was limited by water deficit and not by N deficit.

A ^{15}N study was carried out in plots with 150 kg N ha^{-1} to determine the fate of

applied N. Under aerobic conditions, apparent N recovery was 22% compared to 49% under CS conditions. The ^{15}N balance showed that more applied N was lost through gaseous losses in aerobic plots, and there was hardly any nitrate leaching.

The crop growth model ORYZA2000 was used to calculate seasonal water balances of CS, SNS, aerobic rice, and rainfed regimes for Tuanlin and Los Baños. The model was first parameterized for site-specific soil conditions and cultivar traits and then evaluated using a combination of statistical and graphical comparisons of observed and simulated variables. ORYZA2000 accurately simulated the crop variables, such as leaf area index, biomass, and yield; the same applies for the soil water balance variables, such as field water level and soil water tension in the root zone. The modelling study further revealed that groundwater table depth strongly affected the water-yield relationship for the water saving regimes. For example, rainfed rice did not lead to significant yield reductions at Tuanlin as long as the groundwater table depth was less than 20 cm deep. Simulations for Los Baños conditions with a more drought tolerant cultivar showed that aerobic rice resulted in higher yields than rainfed rice thereby requiring only 420 mm of irrigation. It was found that the soil type influences the irrigation water requirement in CS and SNS regimes. A more permeable soil required around 2000 mm of irrigation water whereas slowly conducive soils required less than half given the local weather and cultivar characteristics for Tuanlin and Los Baños.

The main conclusion of this thesis is that groundwater table depth and soil permeability are more important for the amount of water that can be saved than water saving regimes. Under experimental conditions of low soil permeability and a shallow groundwater table, SNS regimes saved 15−18% of irrigation water as compared to CS without yield reduction. Modelling studies showed that higher savings are possible in more permeable soils when irrigation is fine-tuned with crop demand thereby avoiding water stress during critical growth stages.

The challenge to produce more rice with less water can only be met when N management is optimal. Optimal N supply promotes leaf area growth, biomass growth, grain number and yield per unit land area and reduces evaporative losses. As a result WP_{ET} increases dramatically when water is not limiting. Aerobic soil conditions changed soil-N transformation processes; only when the water regime causes a water deficit, N uptake, crop growth, and yield are reduced.

Optimum water-saving regimes depend on relative (economic) and absolute (physical) water scarcity. In the first case current irrigation practices should be improved by fine-tuning the dose and timing of irrigation to the requirements of a high-yielding crop. In the latter case a transition to aerobic rice systems may be desirable especially if management can be further improved and more suitable cultivars for this system become available. In general, time- and site-specific water management requires a detailed knowledge on crop growth and development, soil hydrological processes, and N cycling in the soil-plant system. A combined experimental and modelling approach is recommended to obtain this knowledge timely and cost effectively.

Samenvatting

Rijst is in Azië het overwegende hoofdvoedsel. De verwachting is dat de vraag naar rijst met 10–20% in de komende 20 jaar zal toenemen rekening houdend met bevolkingsgroei en verandering in consumptiepatroon. De toename in rijstproductie zal moeten komen van een hogere opbrengst per eenheid landoppervlak, want het areaal voor rijstteelt neemt af. Urbanisatie en economische groei veroorzaken een snelle afname van de beschikbare hoeveelheid water voor geirrigeerde landbouw. Rijstboeren in waterschaarse gebieden die afhankelijk zijn van irrigatie, kampen in toenemende mate met watertekorten gedurende het groeiseizoen.

Eén optie om met een verminderde hoeveelheid irrigatiewater om te gaan is de adoptie van waterbesparende regimes op veldniveau. Traditioneel gezien streven boeren naar continue bevloeiing van hun velden om verzekerd te zijn van voldoende watertoevoer voor het droogtegevoelige gewas rijst en om onkruid te bestrijden. In waterbesparende regimes laten boeren de bodem onbevloeid gedurende periodes van enkele dagen, resulterend in afwisselend bevloeid-niet-bevloeide omstandigheden. Gerapporteerde gewasreacties in termen van hoeveelheid waterbesparing en effect op opbrengst zijn variabel.

Meer recent is de ontwikkeling van een nieuw systeem genaamd ‘aerobic rice’ voor gebieden met een hoge frequentie van waterschaarste door onderzoekers van het IRRI en in China. In dit systeem wordt het land niet nat geploegd en blijft de bodem onverzadigd met water zodat rijst geteeld wordt als tarwe of mais. Het verschil tussen aerobic rice en ‘upland rice’ is het gebruik van aanvullende irrigatie, hoogproductieve rassen, kunstmest en bestrijdingsmiddelen. Aerobic rice systemen beogen een relatief hoge en stabiele opbrengst met een waterverbruik van ca. 50% van continue bevloeiing. De waterbesparing vergeleken met continue bevloeiing is dus hoog, maar gaat ten koste van opbrengstvermindering.

Stikstof (N) is de belangrijkste voedingsstof in rijstproductie en limiteert gewasgroei en opbrengst onder bijna alle omstandigheden. Onder continue bevloeiing is N bijna alleen beschikbaar als ammonium, terwijl onder afwisselend bevloeid-niet-bevloeide omstandigheden en aerobic rice, bodembeluchting de nitrificatie zal stimuleren. Een veranderde N-omzetting kan leiden tot hogere N verliezen, gereduceerde N beschikbaarheid en kan gewasgroei en opbrengst beperken.

Waterproductiviteit (WP), berekend als graanopbrengst per eenheid waterverbruik (kg m^{-3}), werd als parameter gebruikt om het effect van waterregime en N niveau te bepalen op waterverbruiksefficiëntie en gewasproductiviteit. Waterverbruik wordt uitgedrukt als evapotranspiratie (ET) of de som van irrigatie en regenval (I+R).

Het hoofddoel van dit proefschrift was het kwantificeren van de effecten van waterbesparende regimes op waterproductiviteit, N gebruiksefficiëntie en opbrengst door een gecombineerde experimentele en modelmatige aanpak. In de studie werd ook de rol van de ondergrondse hydrologie in de schatting van effecten van waterbesparing op de waterbalans onderzocht. Het simulatiemodel ORYZA2000 werd gebruikt om waterbalansen te berekenen voor verschillende water(besparende) regimes. Het model werd ook gebruikt om inzicht te verkrijgen in hoe waterbesparende regimes waterverbruik en opbrengst zouden beïnvloeden onder toekomstige scenario's van diepere grondwaterstanden en hoe het weer en de bodemdoorlatendheid deze relaties zouden beïnvloeden.

Effecten van waterregimes en hoogte van N toediening werden bestudeerd op drie locaties: Tuanlin in Hubei provincie in China, Muñoz op central-Luzon in de Filippijnen en Los Baños in de Filippijnen. Tuanlin en Muñoz zijn gelegen in irrigatiesystemen waar watertekorten in tijd en ruimte optreden. De N toediening bedroeg 0 en 180 kg ha^{-1} in Tuanlin, 0, 90 en 180 kg ha^{-1} in Muñoz en 0 en 150 kg ha^{-1} in Los Baños. De rassen in de experimenten waren voor Tuanlin de hybriden 2You501 en 2You725, voor Muñoz het standaardras IR72 en voor Los Baños het verbeterde upland ras 'Apo'.

In Tuanlin en Muñoz waren de rijstopbrengsten onder bevloeid-niet-bevloeide omstandigheden niet lager dan met continue bevloeiing waarbij het irrigatiewater verbruik 15–18% lager was, resulterend in een significant hogere WP_{I+R} in twee van de drie seizoenen. De (schijn) grondwaterspiegel in dezelfde velden waren ondieper dan 35 cm gedurende het groeiseizoen en in Muñoz was de bodemvochtpotentiaal op 15 cm diepte onder bevloeid-niet-bevloeide omstandigheden niet lager dan −10 kPa waardoor er nauwelijks watertekort voorkwam in deze proeven. In een seizoen met verlaagde grondwaterspiegel in Tuanlin met als gevolg een toename van de interne drainage, waren biomassa, opbrengst en N opname alle wèl gereduceerd. Een analyse van data voor drie seizoenen in Tuanlin liet zien dat de biomassa en N benuttingsefficiëntie lineair afnamen met de duur dat velden niet bevloeid waren.

Tijdens alle seizoenen in Tuanlin met een ondiepe grondwaterstand, verhoogde N toediening de opbrengst significant voornamelijk door een hogere biomassa en het daaraan gerelateerde korrelaantal. Onder condities van geen of een beperkt watertekort, waren de opbrengsten 4.1–5.0 t ha^{-1} en 6.8–9.5 t ha^{-1} voor respectievelijk 0 en 180 kg N ha^{-1}. Opbrengsten waren hoger in Tuanlin dan in Muñoz vanwege een langer groeiseizoen en het gebuik van een hybride cultivar. Bij milde waterstress nam WP_{ET} significant toe door N toediening en variëerde van 0.70 tot 1.17 kg m^{-3} voor 0-N en van 1.27 tot 1.66 kg m^{-3} voor 180 kg N ha^{-1}. Waterbesparende regimes verhoogden WP_{ET} ook onder condities zonder waterstress vanwege een gereduceerde evaporatie.

In Los Baños werd aerobic rice vergeleken met continue bevloeiing. De velden met aerobic rice werden geïrrigeerd wanneer de bodemvochtpotentiaal op 15 cm –30 kPa bereikte. De opbrengst onder aerobe condities met 150 kg N ha^{-1} was gemiddeld 5.3 t ha^{-1}, 27% lager dan onder continue bevloeiing. Irrigatiewater verbruik in aerobic rice was 39% lager dan onder continue bevloeiing, wat leidde tot een hogere WP_{I+R}. Het N gehalte van bladeren met 150 kg N ha^{-1} was bijna gelijk in aerobic rice en continue bevloeiing, wat indiceert dat gewasgroei onder aerobe bodemcondities gelimiteerd was door watergebrek en niet door N tekort.

Een ^{15}N-studie werd uitgevoerd in Los Baños in percelen met 150 kg N ha^{-1} om het lot van toegediende N te bepalen. Onder aerobe bodemcondities was de N benuttingsefficiëntie 22% vergeleken met 49% onder continue bevloeiing. De ^{15}N balans liet zien dat meer toegediende N verloren ging aan de atmosfeer onder aerobe omstandigheden en er nauwelijks nitraatuitspoeling was.

Het gewasgroeimodel ORYZA2000 werd gebruikt om waterbalansen per seizoen te berekenen voor continue bevloeide, afwisselend bevloeid-niet-bevloeide, aerobic rice en voor regenafhankelijke regimes in Tuanlin en Los Baños. Het model werd eerst geparameteriseerd voor locatie-specifieke bodemcondities en raseigenschappen en daarna geëvalueerd met een combinatie van statistische en grafische vergelijkingen van gemeten en gesimuleerde parameters. ORYZA2000 simuleerde de gewasparameters, zoals bladoppervlakte index, biomassa en opbrengst nauwkeurig; hetzelfde gold voor de bodemwaterbalans parameters zoals hoogte van staand water op het veld, en bodemvochtspanning in de wortelzone. De modelstudie toonde verder aan dat het grondwaterniveau de relatie tussen opbrengst en waterbeschikbaarheid sterk beïnvloedde in de waterbesparende regimes. Zo leidde regenafhankelijke rijst niet tot significante opbrengstreducties in Tuanlin als de grondwaterstand minder dan 20 cm diep was. Simulaties voor de Los Baños condities met een meer droogtetolerant ras liet zien dat aerobic rice, waarbij slechts 420 mm irrigatie nodig was, tot hogere opbrengsten leidde dan regenafhankelijke rijst. Verder werd gevonden dat voor de continue bevloeide en afwisselend bevloeid-niet-bevloeide regimes, het bodemtype van invloed was op de benodigde hoeveelheid irrigatiewater. Een meer doorlatende bodem had rond de 2000 mm irrigatie water nodig, terwijl minder doorlatende bodems minder dan de helft nodig hadden voor de weers- en raskarakteristieken van Tuanlin en Los Baños.

De hoofdconclusie van dit proefschrift is dat voor de hoeveelheid water die bespaard kan worden grondwaterstand en bodemdoorlatendheid belangrijker zijn dan waterbesparende regimes. Onder experimentele condities van lage bodemdoorlatend-heid en een ondiepe grondwaterstand, bespaarden bevloeid-niet-bevloeide regimes 15–18% van het irrigatiewater zonder opbrengstreductie vergeleken met continue bevloeiing. Modelstudies lieten zien dat hogere besparingen mogelijk zijn in meer doorlatende bodems als irrigatie wordt afgestemd op de gewasbehoefte waarbij waterstress tijdens kritische groeifases wordt vermeden.

De uitdaging om meer rijst met minder water te produceren kan alleen aangegaan worden wanneer het N management optimaal is. Optimale N voorziening bevordert bladgroei, groei van biomassa, korrelaantal en opbrengst per eenheid landoppervlak en reduceert verliezen door evaporatie. Het gevolg daarvan is dat WP_{ET} sterk toeneemt als water niet limiterend is. Aerobe bodemcondities veranderden bodem-N omzettings-processen; alleen als het water regime een watertekort veroorzaakt, zijn N opname, gewasgroei en opbrengst gereduceerd.

Optimale waterbesparende regimes hangen af van relatieve (economische) en/of absolute (fysische) waterschaarste. In de eerste situatie zouden huidige irrigatie-methoden verbeterd kunnen worden door hoeveelheid en timing van irrigatie beter af te stemmen op de behoeften van hoog-productieve gewassen. In de tweede situatie kan een overgang naar aerobe rijstsystemen wenselijk zijn, vooral als management verder verbeterd kan worden en er meer geschikte rassen beschikbaar komen voor dit system. In het algemeen vereist een tijd- en plaatsspecifiek watermanagement een gedetail-leerde kennis van gewasgroei en -ontwikkeling, bodemhydrologische processen en N kringloop in het bodem-plant system. Een gecombineerde experimentele en modelmatige aanpak wordt aanbevolen om deze kennis tijdig en kosteneffectief te verkrijgen.

PE&RC PhD Education Statement Form

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 22 credits (= 32 ECTS = 22 weeks of activities)

Review of literature (4 credits)
- Water × N interactions in lowland rice (2000)
- Water saving technologies in rice (2000)
- N use and N use efficiency in rice (2000)

Writing of project proposal (2 credits)
- Water × nitrogen interaction and nitrogen economy of lowland rice under water saving irrigation (2000)

Post-Graduate Courses (3 credits)
- Training on use of DNDC model. IRRI (2002)
- Training on use ORYZA2000 model (2002)

Deficiency, Refresh, Brush-up and General Courses (9 credits)
- Ecophysiology of crop production (2000)
- Simulation of crop growth (2000)
- On systems analysis and simulation of ecological processes (2000)
- Scientific writing (2001)

PhD discussion groups (3 credits)
- Discussion group Crop and Weed Ecology (2000-2003)
- IRRI seminar series (2000-2004)

PE&RC annual meetings, seminars and introduction days (0.75 credits)
- Ethics in Science (2002)
- Seminar on use of crop growth models by ARS/USDA, meeting with Timlin and Reddy (2002)
- Global Climate Change & Biodiversity (2003)

International symposia, workshops and conferences (4 credits)
- Aerobic rice. IRRI (2000)
- Water-wise in rice production. IRRI, WUR (2002)
- Active participation in launching of INREF project in Wageningen (2002)
- Master class WUR, co-presenter of seminar ‘Water for food, opportunities for increasing water productivity in agriculture’ (2004)

Laboratory training and working visits (2 credits)
- Analysing soil and plant samples for ^{15}N. IRRI (2003)
- Visit of field experiments in China. Zhejiang University (2000)
- Visit of field experiments in Philippines. NIA, PhilRice (2003)

Curriculum vitae

Paul Belder was born October 28, 1975 in Oud-Alblas, The Netherlands. After finishing secondary school at the Guido de Brès College in Rotterdam, he started his M.Sc. study 'Soil, Water, and Atmosphere' at Wageningen Agricultural University in September 1994. His first M.Sc. thesis was on phosphorus management strategies in rainfed lowland rice systems in Laos. His second thesis was conducted at the laboratory of Theoretical Production Ecology and was about the effect of ethylene on germination of the hemi-parasitic weed *Striga*.

In 2000, he started his Ph.D. research at the Group of Crop and Weed Ecology of Wageningen University. Part of the Ph.D. research was carried out at the International Rice Research Institute in Los Baños in the Philippines. Experiments were carried out at PhilRice in Muñoz, the Philippines and at Tuanlin in China.