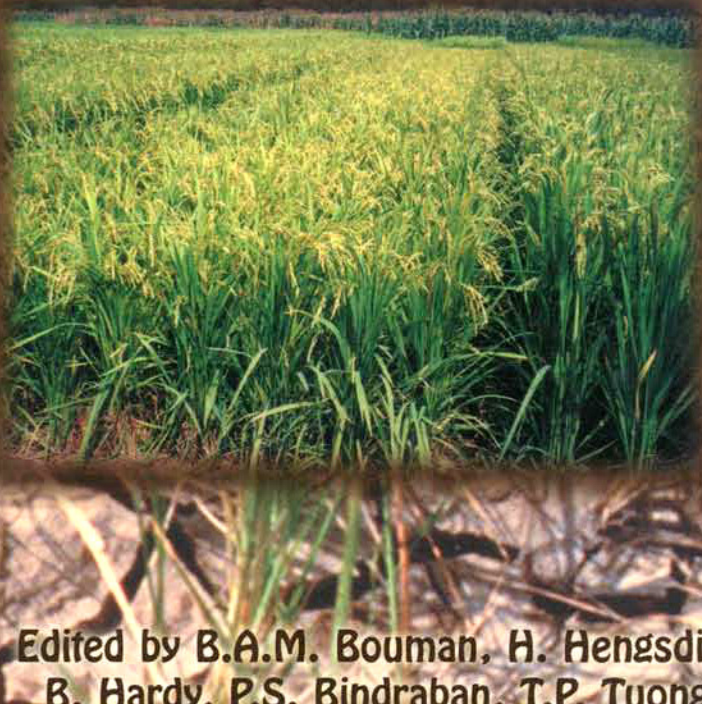
Comprehensive Assessment of Water Management in Agriculture

IPSWAR

Water-wise Rice Production



Edited by B.A.M. Bouman, H. Hengsdijk, B. Hardy, P.S. Bindraban, T.P. Tuong, and J.K. Ladha

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International Platform for Saving Water in Rice

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2002

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The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of 16 nonprofit international research centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR membership comprises Organisation for Economic Cooperation and Development donors, international and regional organizations, and private foundations.

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The responsibility for this publication rests with the International Rice Research Institute.

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Contents

Foreword

Food security in Asia is challenged by increasing food demand and threatened by declining water availability. More than 75% of the annual rice supply comes from 79 million ha of irrigated paddy land. Thus, the present and future food security of Asia depends largely on the irrigated rice production system. However, rice is a profligate user of water. It takes 3,000–5,000 liters to produce 1 kilogram of rice, which is about 2 to 3 times more than to produce 1 kilogram of other cereals such as wheat or maize. Until recently, this amount of water has been taken for granted. Now, however, the water crisis threatens the sustainability of the irrigated rice ecosystem. In Asia, 17 million ha of irrigated rice areas may experience "physical water scarcity" and 22 million ha "economic water scarcity" by 2025. To safeguard food security and preserve precious water resources, ways must be explored to grow rice using less water. Various studies are under way to develop water-saving technologies for rice production, and there is a need to take stock and review the progress.

IRRI, together with Plant Research International of Wageningen University and Research Centre (WUR-PRI; The Netherlands), organized a thematic workshop on Water-Wise Rice Production held 8-11 April 2002 at IRRI, Los Baños, Philippines. The objectives were to present and discuss the state-of-the-art in the development, dissemination, and adoption of water-saving technologies at spatial scales ranging from the field to irrigation system. The workshop brought together scientists and irrigation system managers from several consortia and projects examining water scarcity in rice production: the Water Workgroup of the Irrigated Rice Research Consortium, the Rice-Wheat Consortium, and the projects "Water-less Rice," Growing More Rice with Less Water," and "Ground Cover Rice Production Systems." In total, there were 75 participants from 12 countries. At the workshop, the participants created the International Platform for Saving Water in Rice (IPSWAR; www.irri.org/ipswar/about_us/ipswar.htm). The platform's purpose is to be a mechanism to increase the efficiency and enhance the coherence of research on water savings in rice-based cropping systems in Asia.

This book contains the papers presented at the workshop. One chapter of the book is included as a video on CD-ROM in the back of the book.

Ronald P. Cantrell
Director General

Acknowledgments

The following donors contributed financially to the workshop and to the publication of this book:

- The Swiss Agency for Development and Cooperation through the Water Workgroup of the Irrigated Rice Research Consortium (IRRC). The IRRC was formed in 1999 as a mechanism to promote partnership with national agricultural research and extension systems (NARES) to examine critical issues in rice research and its sustainability. The consortium strengthens regional and NARES-driven multidisciplinary research access, collaboration, and capacity, and provides environmentally and ecologically sound rice production technology for adoption by farmers.
- The Government of The Netherlands, through the Partners in Water for Food program (sponsor of the project Water-less Rice), initiated in the backdrop of the Second World Water Forum, held in 2000 in The Hague. At that meeting, seven challenges were identified, founded on the overriding and generally accepted concept of integrated water resources management. Partners in Water for Food focuses on the challenge of securing the world's food supply, particularly of the poor and vulnerable, in a situation of increasing demand for water. It responds to this challenge through a program of capacity building, knowledge exchange, and cooperation among partners in different countries. In line with integrated water resources management, the program emphasizes the need for comprehensive solutions in managing water demand for food production. The program operates under the theme "capacity building for agricultural water demand management."
- The Comprehensive Assessment of Water Management in Agriculture (CA). The CA is an international research program whose overall aim is to significantly improve our knowledge of water management for agriculture and its effects on the environment, poverty, and food security. The outputs of this research will influence policy and investment decisions for the benefit of poor communities and nature. It will develop analytic tools and extend these findings into the future to help planners and policymakers de-

velop workable strategies that ensure their countries' food and environmental security. The CA is organized through the Consultative Group on International Agricultural Research (CGIAR) Systemwide Initiative on Water Management (SWIM 2). Partners are all interested CGIAR centers with the FAO and other partners (international, regional, and local) that bring environmental, health, and other expertise to this research program.

The overall organizing and technical review committee included, from IRRI, B.A.M. Bouman (chair), T.P. Tuong, R. Lafitte, and J.K. Ladha, and from WUR-PRI, H. Hengsdijk (co-chair) and P. Bindraban. Lou Herrero took care of most of the logistics, with support from Mary Burac, Lucio Caramihan, Ferdie Corcuera, Core Cordon, Ruben Lampayan, and June Madrid.

Intermittent irrigation

Effects of different water management practices on rice growth

Qinghua Shi, Xiaochun Zeng, Muying Li, Xueming Tan, and Fengfeng Xu

This paper describes three experiments conducted in Jiangxi, China, aimed at understanding the performance of rice under different water management practices. Experiment 1 was carried out in rainproof containers to study the response of different varieties (Sanyou 10 and 923 and Zhensan 97B) to three water treatments (flooded, intermittent irrigation, and dry cultivation). Calculated grain yields in the dry-cultivation treatment amounted to 6.3, 6.0, and 3.7 t ha^{-1} for the varieties Sanyou 10 and 923 and Zhensan 97B, respectively. Under intermittent irrigation, yields of Sanyou 10 and 923 were 8% and 10% higher, 9.5 and 8.8 t ha^{-1}, respectively, than under flooded conditions. The highest yield of Zhensan 97B (5.3 t ha^{-1}) was obtained under flooded conditions. Experiment 2, a root-box experiment with different soil water tables, revealed that the treatment with a water table 5 cm below the soil surface produced relatively more roots in the lower soil layers (40–45 cm) than the flooded treatment. Experiment 3 consisted of two field demonstration trials, each with flooded and intermittent irrigation. It turned out that the intermittent irrigation treatments received 48 and 68 mm of irrigation water (i.e., 27% and 37%, respectively) less than the flooded treatments, whereas grain yields increased by 4% to 6%.

Many Asian countries face an increasing scarcity of and competition for freshwater. In addition, in China a serious water shortage is looming: annual water availability is 2,340 m^3 per capita (Wang and Zhou 2000), which is much less than the global average of 7,800 m^3 per capita (Hofwegen and Svendsen 2000).

The dominant practice in rice production is flooded irrigation, which requires large amounts of water, and 70% of total irrigation water used in Chinese agriculture is used for rice production (Luo and Zhang 2001). Currently, the average annual water shortage for irrigation purposes in China is estimated at 3×10^{10} m^3 (Wang and Zhou 2000). Also, other environmental problems are associated with flooded irrigation. For example, flooded rice fields are important sources of methane emission, which is one of the major greenhouse gases associated with global climate change

(Wang et al 1998). In addition, nutrient-use efficiencies in flooded rice are often low because of high losses, resulting in groundwater contamination and high fertilizer costs for farmers. Hence, new water management practices are required to increase water-use efficiency in rice production while maintaining productivity. In addition, such systems may reduce other environmental problems associated with flooded rice production.

Objectives

In this paper, three experiments related to water management in rice production are presented. The objective of the container-experiment 1 is to examine the performance of various rice varieties under different water management practices. The objective of root-box experiment 2 is to examine root morphology under different soil water tables, while experiment 3 consists of two demonstration trials aimed at comparing the performance of rice under flooded and intermittent irrigation at the field scale.

Materials and methods

Experimental design

In experiment 1, three indica rice (*Oryza sativa* subsp. *indica*) varieties—Sanyou 10 (hybrid rice), Zhensan 97B (maintainer line of a three-line hybrid rice), and Sanyou 923 (conventional rice variety)—were grown under three water management regimes: (1) flooded—the soil is kept flooded with 5 cm during the entire growing season, (2) intermittent irrigation till maturity—the soil is drained and kept dry for 2 days between each irrigation with 5 cm standing water, and (3) so-called "dry-cultivation"—the soil is flooded with 5 cm standing water four times during the growing season: at the beginning of the recovery stage, at branch initiation, at heading, and 10 days after heading. The experiment was a randomized complete block design with four replications in 12 plastic-covered concrete containers, each 2.9 m^2. Soil pH was 5.7 and the soil contained 37 g organic matter kg^{-1}, 1.7 g total N kg^{-1}, 40 mg available N kg^{-1}, 30 mg available P kg^{-1}, and 26 mg available K kg^{-1}. Fertilizers were applied according to conventional practices: 40.5 kg P_2O_5 ha^{-1} in the form of calcium-magnesium phosphate as basal dressing, 150 kg N ha^{-1}, of which 50% was applied before transplanting and 25% at tillering and at the booting stage, respectively, and 225 kg KCl ha^{-1}, of which 50% was applied before transplanting and 25% at tillering and at the booting stage, respectively.

Experiment 2 was designed to investigate the morphology of rice roots under different soil water-table levels. Rice seedlings were transplanted into 50 + 50 + 5 cm (height + length + width)-sized plastic root boxes, which were placed in plastic containers with four water-table levels: 5 cm above and 5, 20, and 40 cm below the soil surface. Experiment 2 was in three replicates.

Experiment 3 consisted of two field demonstration trials at the agricultural extension stations of Taihe and Nanchang counties. Each trial included two water treatments: flooded and intermittent irrigation (as described in experiment 1). In Taihe

County, hybrid variety Youcn 647 was used and, in Nanchang County, Zhongyou 288 and coYou 3027 were used. At each site, plot size per variety was 0.15 ha, of which half received a flooded treatment and the other half an intermittent irrigation treatment.

Observations

In experiment 1, tillering dynamics, dry matter production, chlorophyll content, and root activity were measured. The number of tillers was measured at 5-d intervals from transplanting till the booting stage. Biomass production, chlorophyll content, and root activity were measured at the tillering, booting, and heading stage. Chlorophyll content and root activity were measured using the spectrophotometric analysis (Arnon 1949) and α-naphthylamine oxidation method (Zhang et al 1982), respectively. Root activity was measured as the oxidation capacity of roots and expressed in μg α-naphthylamine g^{-1} fresh weight h^{-1}.

Yield components (number of panicles per plant, number of grains per panicle, percentage of filled grains, and 1,000-grain weight) were measured at harvest. Yields were calculated based on 3×10^5 plants ha^{-1} and the measured yield components. In addition, the amount of water applied in each irrigation was measured, enabling the calculation of water-use efficiency (WUE), which is defined here as the grain yield divided by the amount of irrigation water supplied.

In experiment 2, root morphology was examined 30 d after heading, when roots together with the soil were removed carefully from the boxes and rinsed. Subsequently, root samples were taken in 5-cm intervals from top to bottom and oven-dried to determine dry matter distribution.

In demonstration experiment 3, the same yield components were determined as in experiment 1, but, here, actual yields were measured at harvest. As in experiment 1, supplied irrigation water was measured, enabling us to calculate the WUE of the intermittent and flooded treatment. Also, the occurrence of sheath blight was observed, which is a common disease in the area under study and related to water management.

Results

Experiment 1: response of rice varieties to water management

At the maximum tillering stage, the number of tillers per hill in all three varieties was higher in the intermittent irrigation and dry-cultivation treatment than in the flooded treatment (Fig. 1). At the booting stage, the number of tillers was lowest in the dry-cultivation treatments since many tillers died between the maximum tillering and booting stage.

In all three varieties, chlorophyll content at the booting and heading stages was highest in the intermittent irrigation and dry-cultivation treatments (Fig. 2).

At the tillering stage, dry matter production of the three varieties was not much different for the three water treatments (Fig. 3). At the booting and heading stage, dry matter production of Sanyou 10 and 923 was greatest in the intermittent irrigation

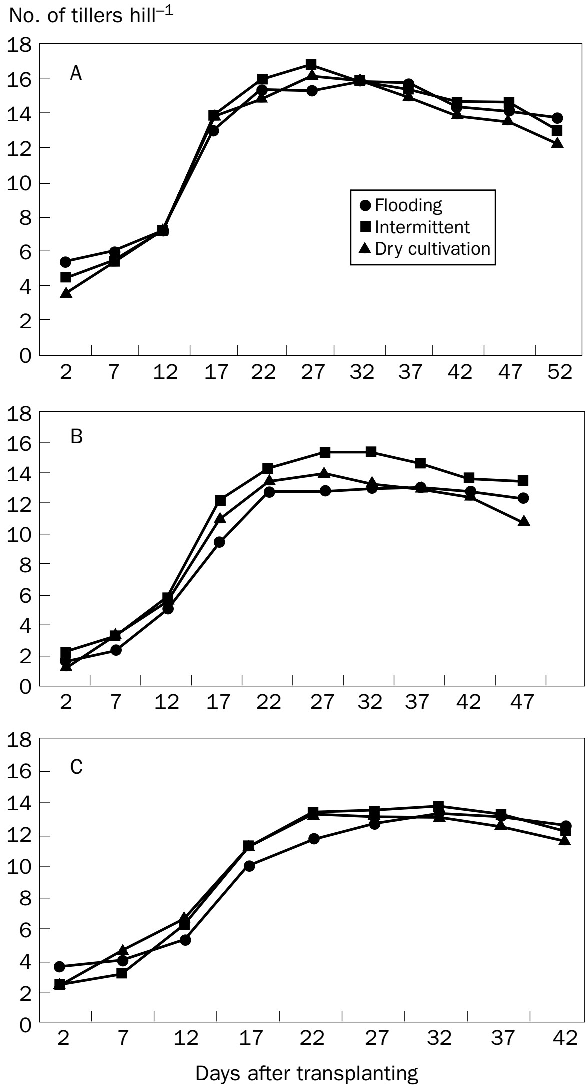

Fig. 1. Development of the number of tillers in flooded, intermittent, and dry-cultivation treatments with the varieties Sanyou 10 (A), Sanyou 923 (B), and Zhensan 97B (C).

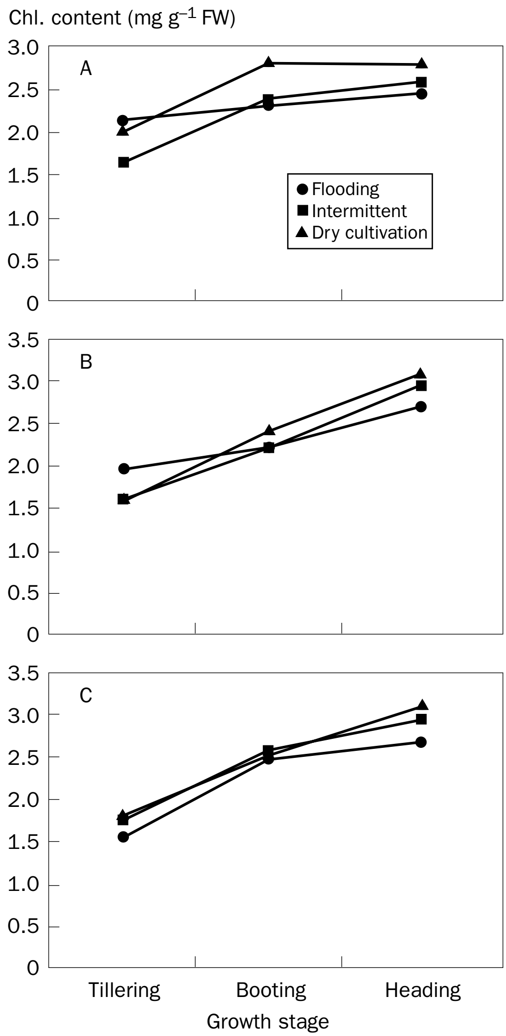

Fig. 2. Chlorophyll content (in mg g^{-1} fresh weight) at tillering, booting, and heading stage in flooded, intermittent, and dry-cultivation treatments with the varieties Sanyou 10 (A), Sanyou 923 (B), and Zhensan 97B (C).

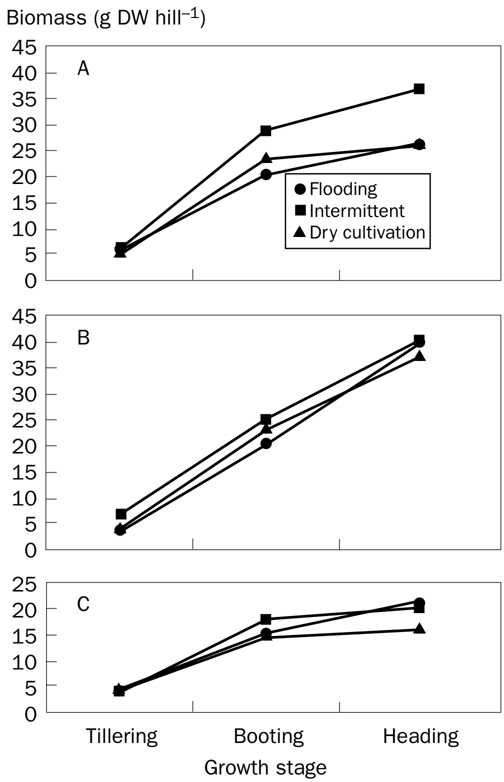

Fig. 3. Biomass (in g dry weight hill^{-1}) at tillering, booting, and heading stage in flooded, intermittent, and dry-cultivation treatments with the varieties Sanyou 10 (A), Sanyou 923 (B), and Zhensan 97B (C).

treatment, whereas, at heading, Zhensan 97B showed the greatest dry matter production under flooded conditions.

From tillering to heading, root activity of the rice varieties was higher in the intermittent irrigation and dry-cultivation treatments than in the flooded treatments (Fig. 4). Perhaps, a better soil aeration contributed to the increased root activity in both the intermittent irrigation and dry-cultivation treatments.

Calculated yields were highest under intermittent irrigation except for Zhensan 97B, which produced better under flooded conditions (Table 1). Yields of Sanyou 10 (9.54 t ha^{-1}) and Sanyou 923 (8.81 t ha^{-1}) under intermittent irrigation were 8% and 10% higher, respectively, than under flooded conditions. Grain yields of all three varieties were lowest in the dry-cultivation treatment: 6.3, 6.0, and 3.7 t ha^{-1} for Sanyou 10, Sanyou 923, and Zhensan 97B, respectively. WUE was highest in the dry-cultivation treatments since yields decreased relatively less than the supplied amount of irrigation water.

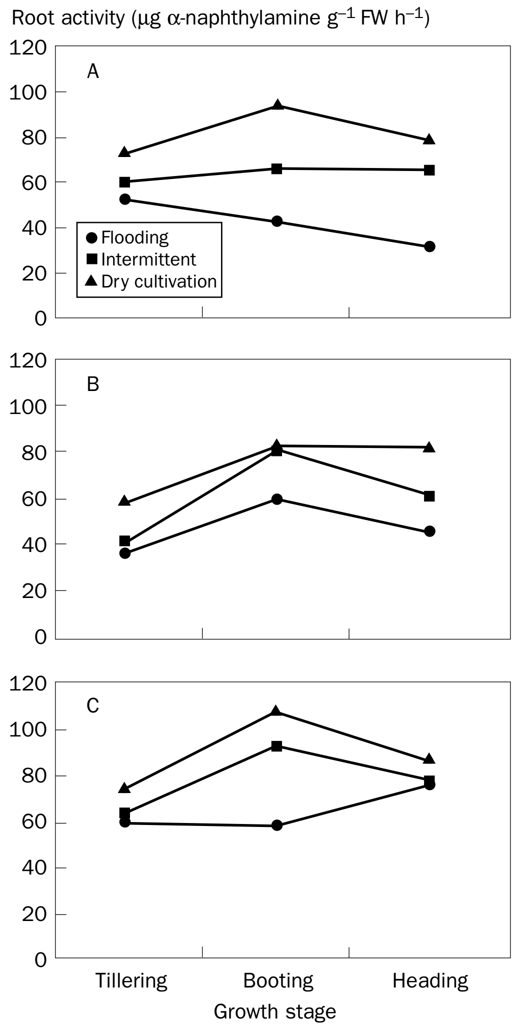

Fig. 4. Root activity (in μg α-naphthylamine g^{-1} fresh weight h^{-1}) at tillering, booting, and heading stage in flooded, intermittent, and dry-cultivation treatments with the varieties Sanyou 10 (A), Sanyou 923 (B), and Zhensan 97B (C).

Table 1. Treatments in experiments 1 and 3 and their effect on yield components, grain yield, and water-use efficiency (WUE, defined here as grain yield divided by the amount of irrigation water supplied).

Variety	Tr.[a]	Supplied irrigation water (mm)	No. of panicles (×1,000 ha^{-1})	No. of grains per panicle	% of filled grains	1,000-grain weight (g)	Yield (t ha^{-1})	WUE (g kg^{-1})
Container experiment (experiment 1)								
A	1	499	3,829	85.5	94.7	28.4	8.81	1.76
A	2	406	4,138	85.9	92.8	28.9	9.54	2.35
A	3	201	2,981	79.2	93.3	28.7	6.32	3.14
B	1	499	3,050	103.1	90.6	28.0	7.98	1.60
B	2	406	3,134	105.5	91.8	29.0	8.81	2.17
B	3	201	2,639	92.3	93.5	26.3	5.99	2.98
C	1	499	3,176	84.5	82.1	24.1	5.31	1.06
C	2	406	2,823	80.6	83.3	23.3	4.41	1.09
C	3	201	2,673	70.7	80.9	24.3	3.71	1.85
Field demonstration (experiment 3)								
D	1	183	2,925	131	91.6	28.0	6.51	3.56
D	2	115	3,000	136	91.6	27.6	6.86	5.97
E	1	183	3,150	120	95.8	28.6	7.21	3.94
E	2	115	3,180	129	92.2	27.8	7.52	6.54
F	1	175	3,240	118	81.3	24.8	6.81	3.89
F	2	127	3,315	117	83.8	25.1	7.17	5.65

[a]Tr. = water treatment; Varieties A: Sanyou 10; B: Sanyou 923; C: Zhensan 97B; D: Zhongyou 288; E: coYou 3027; F: Youcn 647; Tr. 1: flooding irrigation; Tr. 2: intermittent irrigation; Tr. 3: dry cultivation.

Experiment 2: root morphology under different soil water tables

Only the treatment with a water table 5 cm below the soil surface produced relatively more roots in the lower soil layers (40–45 cm) than in the flooded treatment (Fig. 5), although the difference is small. At the time of observation, 30 d after heading, we did not observe root degeneration in the flooded treatment as reported by Kar et al (1974). Root production in the treatments with soil water tables 20 and 40 cm below the soil surface was more concentrated in the upper 5 cm below the soil surface compared with that of both other treatments. Most likely, treatments with soil water tables 20 and 40 cm below the soil surface suffered too much drought stress to reach lower soil layers (Fig. 6). Total aboveground biomass production in treatments with soil water tables 5 cm above and below the soil surface was almost the same, whereas root biomass production in the treatment with a soil water table 5 cm below the soil surface was slightly higher.

Experiment 3: performance of rice crops under flooded and intermittent irrigation

In Nanchang County, intermittent irrigation treatments with Zhongyou 288 and coYou 3027 received 68 mm (37%) irrigation water less than the flooded treatment, whereas rice yields were 5% and 4% higher, respectively (Table 1). In Taihe County, Youcn

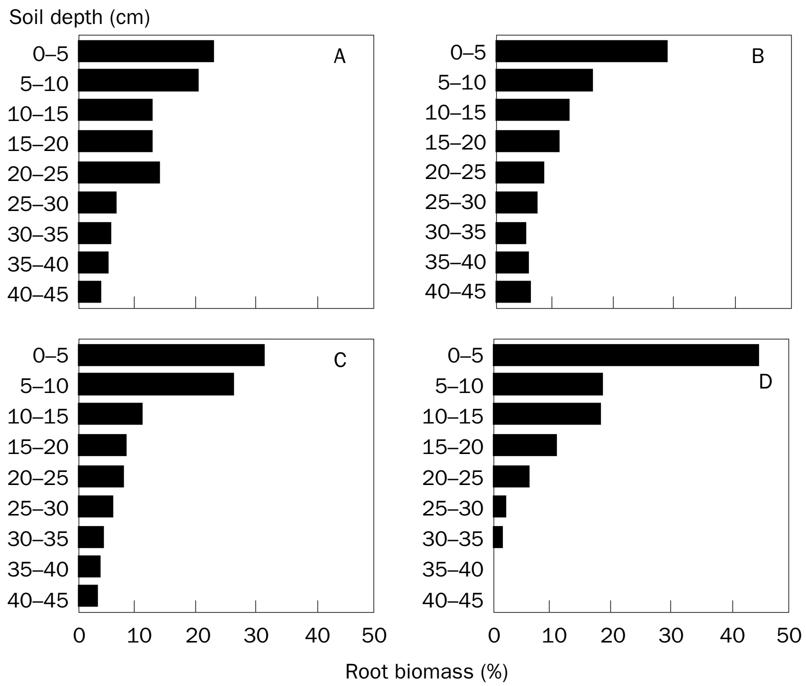

Fig. 5. Root dry matter distribution in 5-cm soil layers for water tables 5 cm above the soil surface (A) and 5 (B), 20 (C), and 40 (D) cm below the soil surface, respectively. On the X-axis, percentage dry matter, and on the Y-axis, soil depth in 5-cm layers.

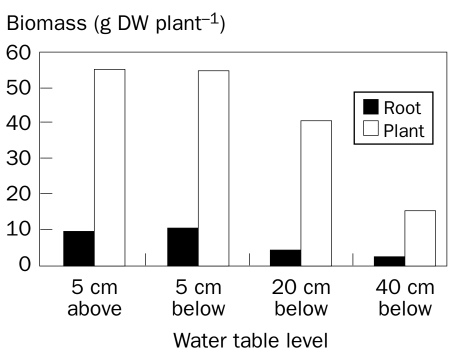

Fig. 6. Effect of different water tables on above- and underground biomass production (in g dry weight plant^{-1}) of rice in experiment 2.

647 received in the intermittent irrigation treatment 48 mm (27%) of irrigation water less than in the flooded treatment, while its yield was 6% higher. WUE of intermittent irrigation treatments was on average 61% higher than that of flooded treatments.

Regular field monitoring in the demonstration trials showed that the occurrence of rice sheath blight was about 14% lower in the intermittent irrigation treatments, which may have contributed to the higher yields.

Conclusions and discussion

Based on the results of the demonstration trials (experiment 3), we conclude that intermittent irrigation in rice cultivation may reduce irrigation water use considerably (27–37%) compared with flooded rice cultivation, while at the same time yields increase slightly (4–6%). Also in experiment 1, intermittent irrigation was associated with a similar yield increase of varieties Sanyou 10 and 923. Only Zhensan 97B produced better under flooded conditions, which indicates that varieties respond differently to water management. The dry-cultivation treatment showed the worst yield performance for all three tested varieties. Rice plants grown under intermittent irrigation management have higher root activity, produce more tillers per hill and biomass, and, in general, their leaves have a higher chlorophyll content.

Previous studies showed that variety Sanyou 63 and other hybrid varieties have a high nutrient uptake capacity under water-stress conditions (Yang et al 1996, Wang et al 2000). In addition, Sanyou 63 has a strong tolerance of drought (Yang et al 1995, 2002). In experiments 1 and 3, yields of all four hybrid varieties increased under intermittent irrigation compared with flooded conditions, indicating that these hybrid rice varieties are well adapted to intermittent dry-wet conditions.

In experiment 2, treatments with water tables 20 and 40 cm below the soil surface showed drought-stress symptoms and roots did not penetrate to deep soil layers as in the treatment with a water table 5 cm below the soil surface. Lafitte and Bennett (this volume) also reported that some rice varieties cease root development in response to drought stress. The treatment with a water table 5 cm below the soil surface showed a slightly higher root biomass production and relatively more roots in deep soil layers (40–45 cm) than in the flooded treatment. Higher yields in the intermittent irrigation treatments may be related to better root development, which facilitates nutrient uptake from deep soil layers. Further research is required to confirm this theory.

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Notes

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The effects of irrigation management on yield and water productivity of inbred, hybrid, and aerobic rice varieties

G. Lu, R. Cabangon, T.P. Tuong, P. Belder, B.A.M. Bouman, and E. Castillo

The objective of this study was to compare the effects of water-saving irrigation regimes on yield, irrigation water input, water balance components, and water productivity of aerobic and conventional rice varieties. The experiments were carried out in Tuanlin, Hubei Province, and in Huibei, Henan Province, China. The main plots at each site were irrigation water management regimes, ranging from rainfed to irrigated continuously flooded. In the subplots, hybrid rice variety 2you725 was compared with aerobic rice variety HD502 at Tuanlin and inbred variety 90247 with aerobic rice variety HD502 at Huibei. The experiment in Tuanlin included two N-fertilizer treatments (180 kg N ha^{-1} and no N fertilizer) in the sub-subplots. The aerobic rice variety at Tuanlin was heavily infested with stem borer, while that at Huibei yielded significantly less than the inbred rice variety because of reduced tillering and duration in all water regimes. Continuous flooding had the highest irrigation water inputs, followed by alternate wetting and drying irrigation, saturated soil culture in raised beds, flush irrigation in aerobic soil, and rainfed treatments. Rice yields did not differ significantly among water treatments. Flush irrigation and rainfed rice had the highest irrigation and total water productivity. The lack of significant differences in rice yield between water treatments was probably due to shallow groundwater tables at both sites. The shallow groundwater table depth in these experiments has implications for extrapolating the effects of the water-saving irrigation treatments to larger spatial scales.

Irrigated land produces 96% of the annual volume of rice in China (China Agricultural Almanac 2000) and uses more than 50% of all freshwater developed in Asia (Barker et al 1999). Because of continued population growth and economic development, the demand for freshwater to meet industrialization and domestic needs is growing rapidly. It is expected that, in the near future, less water will be available for rice cultivation (Tuong and Bouman 2002). Water savings and “producing more rice with less water” are crucial for food security in China.

Several water-saving irrigation techniques for rice have been reported previously (Bouman 2001, Bouman and Tuong 2001). The most widely adopted water-saving practice in China is alternate wetting and drying (AWD) (Mao Zhi 1993, Li 2001, Xu Zhifang 1982). The rice field is allowed to dry for a few days in between irrigation events, including a midseason drainage in which the field is allowed to dry for 7–15 days at the end of the tillering stage. The potential of AWD to reduce water input and its effect on yield and water productivity depend on soil type, groundwater table depth, and climate (Bouman and Tuong 2001).

Tabbal et al (2002) reported reduced water inputs and increased water productivity of rice grown under just-saturated soil conditions, compared with traditional flooded rice. Borrell et al (1997) reported that, in semitropical Queensland, Australia, saturated soil culture with rice grown on raised beds (SSC-RB) reduced the amount of irrigation water by about 32% compared with conventional methods. This system involves growing rice on raised beds with a shallow water table (about 10 cm below the surface of the beds) by maintaining a shallow water depth in the furrows. In a semiarid environment, Thompson (1999) reported no gain in water productivity with SSC-RB since both irrigation input and yield declined by 10%.

It has been suggested that rice could be grown aerobically under irrigated conditions just like upland crops, such as wheat or maize (Bouman 2001). The aerobic condition is maintained by using flush irrigation (FI) or sprinklers so that ponding occurs for only short periods of time just after irrigation or rain, if at all. The potential for water savings is large, but aerobic cultivation using conventional lowland rice varieties almost always leads to yield reduction (De Datta et al 1973, McCauley 1990, Westcott and Vines 1986). A special type of rice is required to produce high yields under nonflooded conditions in nonpuddled and unsaturated (aerobic) soil. Bouman (2001) named this "aerobic rice"; it is responsive to high inputs, can be rainfed or irrigated, and tolerates occasional flooding. A first generation of high-yielding aerobic rice varieties has been developed successfully over the last 20 years in China (Wang Huaqi et al, this volume). However, the trade-off between yield reduction and water savings compared with flooded lowland rice is still unknown (Yang Xiaoguang et al, this volume).

This study aimed to quantify the effects of different irrigation water management regimes, ranging from rainfed to continuous flooding, on growth, yield, and water productivity of conventional and aerobic rice varieties in two contrasting soil-hydrological environments in China.

Materials and methods

The experiments were conducted in Huibei, near Kaifeng, in Henan Province (from June to October 2001) and in Tuanlin, near Jingmen, in Hubei Province (from May to September 2001), China. The soil conditions at the two sites are given in Table 1.

In Tuanlin, the experiment was conducted in a split-split-plot design with three replicates. The main plots were four water treatments:

Table 1. Soil characteristics of 20-cm topsoil, Huibei and Tuanlin, 2001.

Item	Huibei[a]	Tuanlin
Soil type	Loam	Clay loam
pH (1:1 H_2O)	na	6.5
Organic carbon (%)	na	1.03
Available N (mg kg^{-1})	na	5.8
CEC (cmol kg^{-1})	na	20.6

[a]na = not available.

1. *Alternate wetting and drying (AWD) in puddled soil*. The field was kept dry for several days after the disappearance of ponded water before irrigation was reapplied, as described in Cabangon et al (2001). This included a period of midseason drainage by withholding irrigation water for 10–15 days around midtillering (no active drainage). In Tuanlin, this version of AWD is the current farmers' practice.
2. *Flush irrigation (FI) in nonpuddled aerobic soil*. Plots were irrigated to cover the field with a layer of 40–80 mm of water, which quickly infiltrated into the soil. Irrigation was reapplied when the soil water potential at 20-cm depth reached –50 kPa.
3. *Partially rainfed (PRF) in puddled soil*. No irrigation water was applied from 10 days after transplanting (DAT) onward.
4. *Saturated soil culture on raised beds (SSC-RB)*. Rice was transplanted on beds (about 0.9 m wide), separated by furrows (30 cm wide and 30 cm deep). Irrigation was applied when the water level in the furrows fell 20 cm below the surface of the beds to bring the water level back to that of the bed surfaces.

In all four treatments, fields were kept flooded with 2–5-cm water depth for about 10 DAT. Rainfall was used as much as possible and irrigation was applied only as needed. The subplots consisted of two varieties: a commonly grown hybrid rice, 2you725, and an aerobic rice, HD502 (Wang Huaqi et al, this volume). The establishment method was carefully selected to give the best results for the specific variety, using local experience and expert knowledge (Wang Huaqi, personal communication for aerobic rice). The hybrid rice 2you725 was transplanted using 43-d-old seedlings at 2 plants $hill^{-1}$ in 20 × 20-cm spacing. The aerobic rice HD502 was transplanted using 29-d-old seedlings at 4 plants $hill^{-1}$ in 27 × 13-cm spacing. The sub-subplots consisted of two levels of nitrogen (N) fertilizer application: no N fertilizer (N_1) and 180 kg N ha^{-1} (N_2) applied in four splits as 30% basal, 30% at 10 DAT, 30% at panicle initiation (PI), and 10% at heading. In addition, 70 kg P ha^{-1} and 70 kg K ha^{-1} were applied as basal application. In AWD, FI, and PRF, basal fertilizer was broadcast and incorporated into the soil during the last land preparation (harrowing). In SSC-RB, basal fertilizer was broadcast and manually incorporated at transplanting. The topdressings were applied on the soil surface just before irrigation or rainfall.

In Huibei, the experiment was carried out in a split-plot design with three water regimes as the main plots and variety subplots in four replications. The water treatments were continuous flooding (CF), AWD, and FI. In the CF treatment, the soil was puddled and kept continuously flooded with a shallow (2–5 cm) water layer. In Huibei, CF is the current farmers' practice. The AWD (puddled soil) and FI (nonpuddled soil) treatments were the same as in Tuanlin. The rice varieties used were a local inbred commonly grown in Huibei, 90247, and an aerobic variety, HD502. The inbred rice 90247 was transplanted using 37-d-old seedlings at 2 plants $hill^{-1}$ in 20 × 20-cm spacing. The aerobic rice HD502 was transplanted using 27-d-old seedlings at 4 plants $hill^{-1}$ in 27 × 13-cm spacing.

Daily meteorological parameters (rainfall, pan evaporation, sunshine hours, temperature—minimum and maximum—and wind speed were collected from meteorological stations at the site in Tuanlin and some 15 km away from the site in Huibei. At both sites, the following hydrological measurements were made following procedures described in Cabangon et al (2001): irrigation water input using flow meters at each irrigation (in all plots in Tuanlin, in main plots in Huibei), daily standing water depth using meter gauges (in all plots in Tuanlin and in Huibei), daily percolation rate using PVC percolation rings (five rings in AWD and six rings in PRF in Tuanlin; one ring each in AWD and PRF plots in Huibei), and groundwater depth (in each replicate in the bunds, at infrequent time intervals in Tuanlin and twice weekly in Huibei). In Tuanlin, irrigation water and surface drainage were measured in individual sub-subplots, whereas in Huibei these were measured in the main plots. The amount of surface drainage was calculated from the difference in the ponded water depth before and after drainage. The seasonal amount of percolation was computed as the sum of measured daily percolation rates. It was assumed that there was no percolation during days without standing water. The seasonal seepage (defined as lateral flow of water through and underneath bunds from one field to another) was estimated as the closure term in the water balance over the whole season: seepage = rainfall + irrigation – percolation – surface drainage – evapotranspiration. Note that, in this calculation, the computed seepage incorporates the error term and, implicitly, any capillary rise. Evapotranspiration was computed from the weather data using the Penman equations (Allen et al 1998). At 15 DAT, PI, flowering, and maturity, 12-hill samples were collected to measure total biomass and biomass components (leaves, stems, panicles), following the procedures described in Cabangon et al (2001). At maturity, we also measured grain yield and yield components (1,000-grain weight, spikelet number, panicle number, filled spikelet numbers). Water productivity was calculated as the weight of grain per unit of water used (g grain kg^{-1} water). The following values were computed:

- WP_I: yield per unit of irrigation water from transplanting to harvest
- WP_{I+R}: yield per unit of irrigation and rainfall water from transplanting to harvest

Results

Climatic and agrohydrological conditions

Rainfall, pan evaporation, and sunshine hours from transplanting to harvest are shown in Table 2. These parameters are different for the two varieties at each site because they had different transplanting dates and crop growth durations. Rainfall was lower in Tuanlin than in Huibei. There was hardly any difference in seasonal evaporation between the two sites, although the amount of sunshine hours was about twice as large in Tuanlin as in Huibei.

Figure 1 gives the dynamics in groundwater table depths. In Huibei, the groundwater table fluctuated from 0- to 20-cm depth during most of the crop growth period and started to decline some 2 wk before the harvest of 90247 at the time of drainage of the fields (Fig. 1). At the time of harvest of 90247, the groundwater table was around 75-cm depth. In Tuanlin, the groundwater table was slightly deeper during the crop growth period, and varied mostly from 20- to 40-cm depth until 2 wk before harvest, when it dropped to 80-cm depth.

Figure 2 gives the dynamics in field-water depths (ponded water) for AWD and FI at Tuanlin (the PRF and SSC-RB treatments had intermediate field-water depths and are not shown) and for all treatments at Huibei. In Tuanlin, all four water regimes had a similar pattern: flooded conditions from transplanting till about midtillering (1), then predominantly nonflooded conditions until a few days before flowering (2), then flooded conditions until terminal drainage some 2 wk before harvest (3), and finally nonflooded conditions until harvest (4). In the nonflooded periods, the field-water table dropped below the surface but did not go deeper than about 15-cm depth. The predominantly nonflooded period (2) included the midseason drainage. AWD had the highest field-water depth at all times and FI the lowest. In the FI treatment, most of the root zone was saturated and aerobic conditions were not achieved. The number of days with flooded conditions was highest in AWD and statistically the same in all three other treatments (Table 3). In Huibei, the three water treatments also had similar floodwater depth dynamics (Fig. 2B). However, the conditions were much wetter than in Tuanlin. The AWD treatment almost always had some floodwater, and FI was generally only nonflooded after flowering. Even then, the field-water table never went deeper than 6 cm so that aerobic soil conditions were barely obtained. The

Table 2. Weather data and crop duration from transplanting to harvesting at Huibei and Tuanlin, 2001.

Site	Variety[a]	Rainfall (mm)	Pan evaporation (mm)	Sunshine (h)	Duration (d)
Huibei	90247	360	437	427	119
Huibei	HD502	354	398	360	103
Tuanlin	2you725	297	434	769	110
Tuanlin	HD502	221	409	716	96

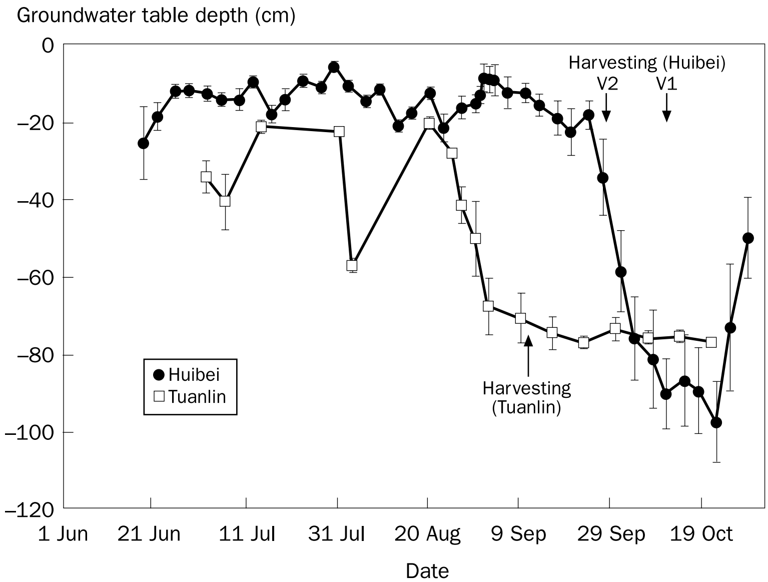

Fig. 1. Mean ± SE (N = 4 at both sites) groundwater table depth in Tuanlin and Huibei, 2001.

number of days with flooded conditions was highest in CF, followed by AWD and FI (Table 3). In general, the number of days with flooded conditions was about twice as high in Huibei as in Tuanlin.

Grain yield

In Tuanlin, the yield of the hybrid rice variety was significantly higher than that of the aerobic rice variety in all water treatments and at both N levels (Fig. 3A). The extremely low yields of the aerobic variety were caused by heavy stem borer infestation after flowering. At flowering, total biomass (averaged over the four water treatments) of the aerobic rice was still 62% of that of the hybrid rice in the zero-N treatment and 56% in the 180 kg N ha^{-1} treatment, whereas, at harvest, this had dropped to 23% and 32%, respectively (data not shown). Because of this stem borer infestation, the aerobic rice data are excluded from further analysis. The hybrid rice yields in plots with 180 kg N ha^{-1} fertilizer were significantly higher ($P < 0.01$) than in plots without N application ($P < 0.01$). This conforms to previous findings by Cabangon et al (2001). In the treatments without N fertilizer, there were no significant differences among the four water treatments. In the N-fertilized plots, AWD had the highest grain yields, which were significantly higher than those of SSC-RB, which had the lowest yields. The yields of AWD, PRF, and FI did not differ significantly from each other ($P <$ 0.05), nor did those of PRF, FI, and SSC-RB. The low yield of SSC-RB might have been caused by its lower hill density (21 hills m^{-2}) compared with those of all other treatments (about 25 hills m^{-2}).

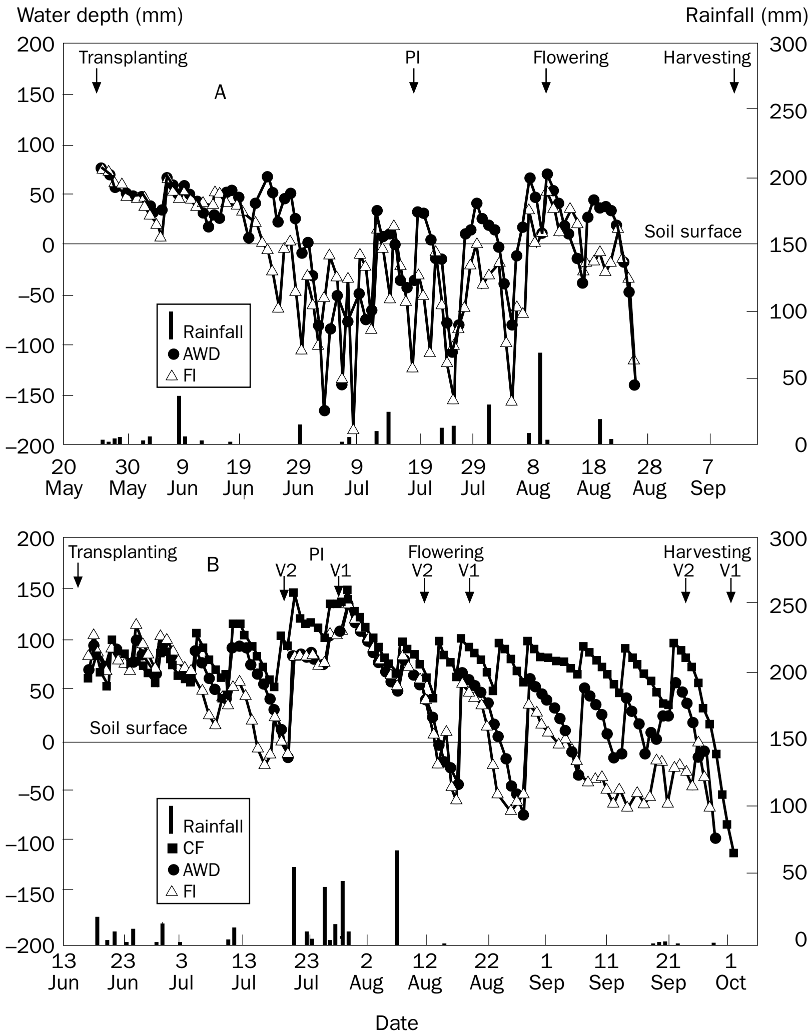

Fig. 2. Mean ± SE field-water depths in Tuanlin (A) (N = 6, in hybrid rice, from two nitrogen treatments and three replicates) and in Huibei (B) (N = 6 from two varieties and three replicates). AWD = alternate wetting and drying, FI = flush irrigation, CF = continuous flooding, PI = panicle initiation, V1 = hybrid rice in Tuanlin and inbred rice in Huibei, and V2 = aerobic rice at both sites.

Table 3. Number of days with standing water in the field, Huibei and Tuanlin, 2001.

Treatment	Tuanlin[a]	Huibei[b]
Continuous flooding	–	104 ± 1
Alternate wetting and drying	49 ± 4	87 ± 4
Flush irrigation	32 ± 4	74 ± 8
Partially rainfed	33 ± 5	–
Raised beds	33 ± 4	–

[a]N = 12 (from two varieties, two N treatments, and three replicates). [b]N = 6 (from two varieties and three replicates).

In Huibei, the local inbred variety had significantly higher yields ($P < 0.01$) than the aerobic variety (Fig. 3B). This may be attributed to a lower tillering ability (data not shown) and a shorter duration (103 d for the aerobic variety versus 119 d for the inbred; Table 2) of the aerobic variety compared with the inbred variety. There was no significant difference in yield among the three water treatments in either of the two rice varieties.

Water balance

Figure 4 shows the water balance components for the different water treatments in Tuanlin (Fig. 4A) and Huibei (Fig. 4B) in the period from transplanting to harvest. In Tuanlin, data are given only for the hybrid rice treatments. The total water input (rainfall + irrigation) ranged from 320 to 750 mm, of which 297 mm was rainfall. The irrigation water input in AWD was significantly the highest of all treatments, whereas that in SSC-RB was significantly higher than those in FI and PRF, which were statistically the same ($P < 0.01$). The small amount of irrigation in PRF was applied in the first 10 DAT. The daily percolation rate ranged from 0.5 to 1.0 mm d^{-1} and averaged 0.7 mm d^{-1}. These low percolation rates are attributed to the shallow groundwater table (Fig. 1). Summed over the whole season, the percolation loss was 40 mm in AWD and about 30 mm in the other three treatments (statistically all the same). There was no drainage outflow because rainfall was very low during the season. The (calculated) seasonal seepage loss was considerable in AWD and SSC-RB. However, the seepage was negative in PRF and FI, indicating that these treatments received seepage water from the surroundings.

In Huibei, the total water input (rainfall + irrigation) ranged from 569 to 934 mm, of which 354 mm was rainfall (Fig. 4B). The differences in irrigation and total water inputs were statistically significant among all three water treatments ($P < 0.01$), with CF having the highest values and FI the lowest. The daily percolation rates ranged from 0.2 to 1.4 mm d^{-1}, averaging 0.7 mm d^{-1}. Summed over the whole season, percolation loss was 73 mm in CF, 62 mm in AWD, and 52 mm in FI (statistically

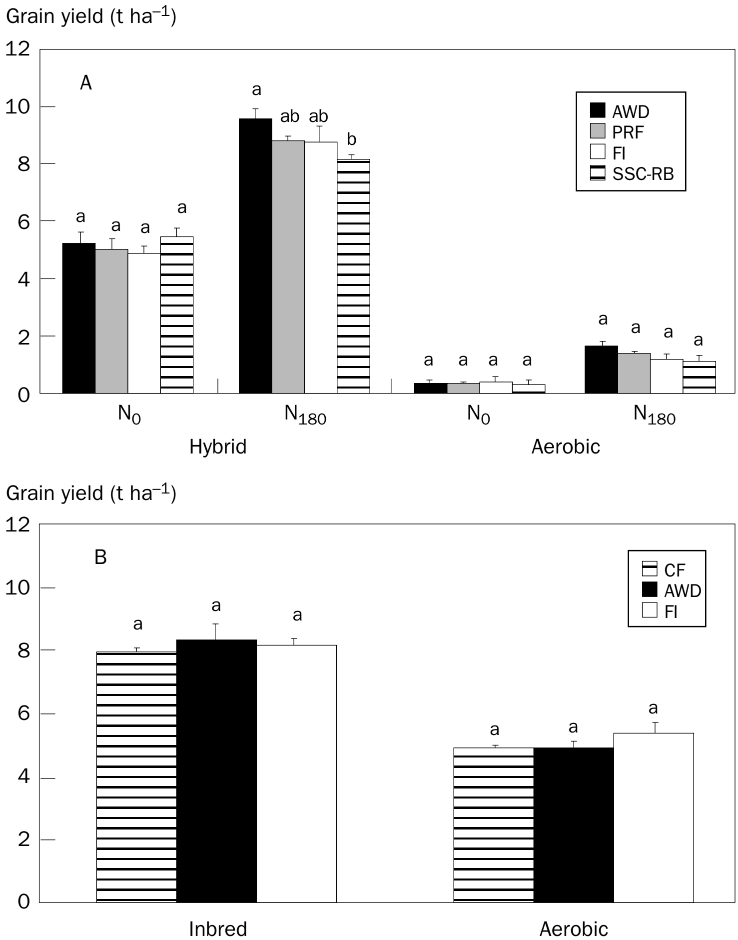

Fig. 3. Mean grain yields in Tuanlin (A) and Huibei (B). AWD = alternate wetting and drying, PRF = partially rainfed, FI = flush irrigation, SSC-RB = saturated soil culture in raised beds, and CF = continuous flooding. N_0 = zero nitrogen and N_{180} = 180 kg N ha^{-1}. In each N treatment in (A) and each variety in (B), columns with the same letters are not significantly different at the 5% level.

all the same). There was no significant difference in percolation loss between the two varieties (data not shown). As in Tuanlin, the low percolation rates are attributed to the shallow groundwater table. The mean seasonal surface drainage in CF was significantly higher than in AWD and FI, which were able to make more effective use of rainfall than CF. There were net seepage outflows in all treatments. CF had significantly the highest seepage loss and FI the lowest. There were no significant differences in seepage between the two varieties.

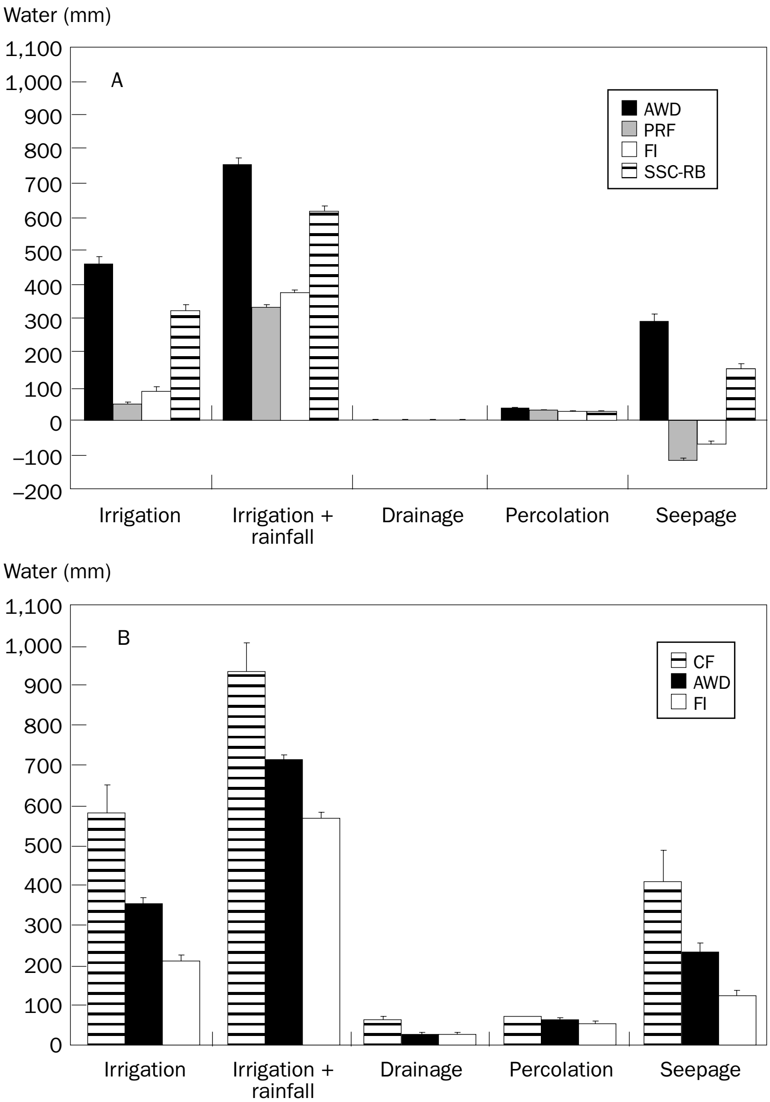

Fig. 4. Mean water balance components in the period from transplanting to harvest in Tuanlin (A) (N = 6, in hybrid rice, from two N treatments and three replicates) and in Huibei (B) (N = 6, from two varieties and three replicates). AWD = alternate wetting and drying, PRF = partially rainfed, FI = flush irrigation, SSC-RB = saturated soil culture in raised beds, and CF = continuous flooding.

Water productivity

In Tuanlin, the total water productivity, WP_{I+R} (for hybrid rice), ranged from 0.8 to 2.4 kg m^{-3}, whereas the irrigation water productivity, WP_I, ranged from 1 to 16 kg m^{-3} (Fig. 5A). The WP_{I+R} values are relatively high compared with those in the literature (see Bouman and Tuong 2001 for review data) and are explained by the combination of relatively high yields and low water inputs. The extremely high values of WP_I in PRF and FI were caused by the extremely low irrigation inputs in these treatments (Fig. 4A). With a water table at 6 cm or less below the soil surface, the roots could extract water directly from the groundwater. Among the four water treatments, PRF had the highest WP_{I+R} and WP_I and AWD had the lowest. The differences between PRF and FI, and between AWD and SSC-RB, were not significant.

In Huibei, WP_{I+R} ranged from 0.87 to 1.45 kg m^{-3} in inbred rice and from 0.54 to 0.95 kg m^{-3} in aerobic rice (Fig. 5B). Because of their higher yields, WP_{I+R} was higher in the inbred rice than in the aerobic variety in all water treatments. The differences among the water treatments were significant: FI had the highest and CF the lowest WP_{I+R} in both the inbred and aerobic variety. The relative trends and differences in irrigation water productivity were the same as in total water productivity.

Conclusions and discussion

The aerobic rice variety HD502 used in our experiments was primarily bred for, and tested in, temperate zones of China (Wang Huaqi et al, this volume). The relatively high yields (around 5 t ha^{-1}) we obtained in Huibei are an indication that aerobic rice varieties can also be grown in subtropical environments. The lower yield of the aerobic variety compared with the inbred variety was related to its shorter duration and lower tillering capacity. One way to enhance the yield of aerobic rice may be to increase plant density. On the other hand, a shorter duration may have other advantages compensating for the lower yield, such as allowing earlier establishment of a postrice crop and thereby increasing its yield, and perhaps increasing total system productivity and/or water productivity.

In Tuanlin, the very low yield of aerobic rice was caused by heavy stem borer infestation after flowering. Before the infestation, the crop had developed very well. Aerobic varieties that are more resistant to stem borer and proper pest management may result in higher yields. The heavy stem borer infestation in our experiment may also have been caused by the “island effect.” The aerobic rice flowered later than the surrounding hybrid rice and may have been an especially attractive target for stem borers (K.L. Heong, personal communication, July 2002). Synchronizing the flowering time of aerobic rice with that of the other varieties in the area, through a change in establishment time, may help reduce the risk of pest infestation.

Water-saving irrigation, especially flush irrigation and partially rainfed systems, can significantly reduce the amount of irrigation compared with farmers’ practices, without affecting rice yield. This implies that there is a possibility for irrigation system managers to reduce the amount of water diverted to rice at the study sites. These findings and their implications, however, are site-specific and care must be taken in

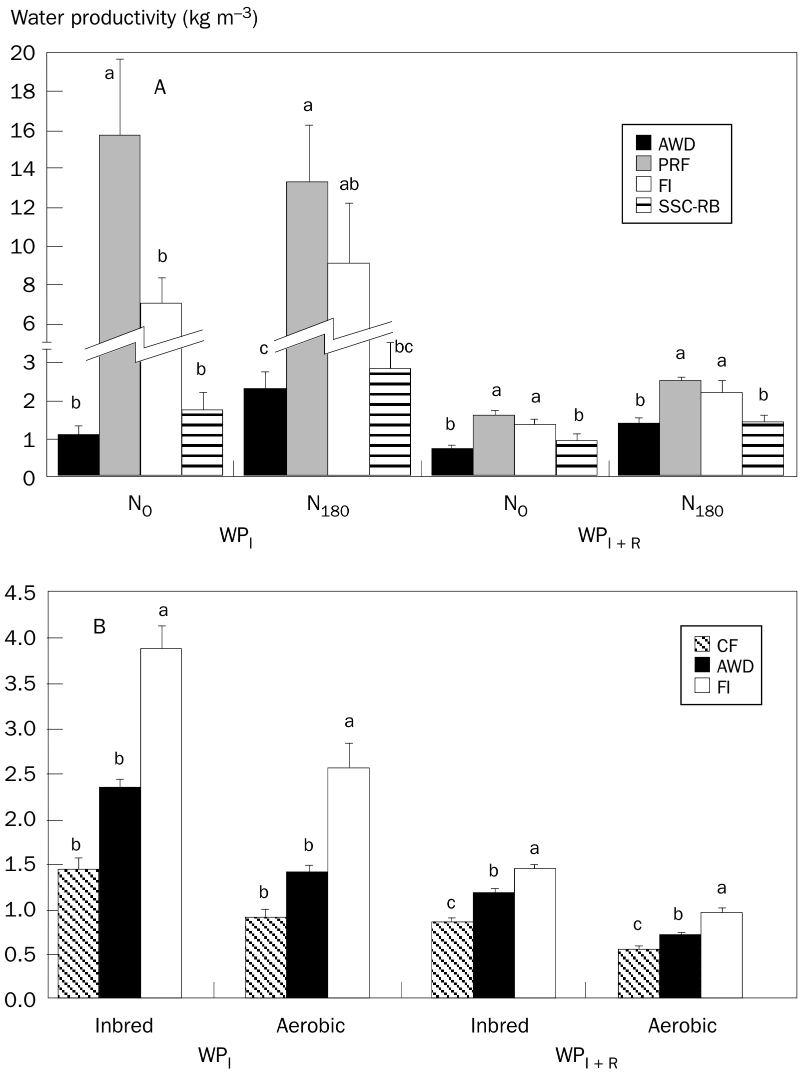

Fig. 5. Water productivities with respect to irrigation (WP_I) and total water input (WP_{I+R}) in different water and nitrogen treatments (in hybrid rice) in Tuanlin (A) and in different water treatments and varieties in Huibei (B). AWD = alternate wetting and drying, PRF = partially rainfed, FI = flush irrigation, SSC-RB = saturated soil culture in raised beds, and CF = continuous flooding. In each nitrogen treatment in (A) and variety in (B), columns with the same letters are not significantly different at the 5% level.

extrapolation. First, our results were obtained in relatively small subplots in farmers' fields that allowed us to keep irrigation time short and the irrigation application efficient. In larger fields, the irrigation time is longer, which may result in larger seepage and deep-percolation losses. Second, at our sites, the groundwater tables were very shallow and the rice plants could directly take up groundwater to meet their demand for transpiration. More study is needed on the interaction between irrigation and groundwater table depths before recommendations for large-scale application of water-saving irrigation techniques can be made. The shallow groundwater tables at our experimental sites may be the result of continuously ponded water in surrounding rice fields that recharge the groundwater through deep percolation. With the wide-scale adoption of water-saving irrigation techniques, the groundwater tables may go down because of less groundwater recharge from the rice fields. Furthermore, seepage from unlined irrigation canals in our study areas may also recharge groundwater. Reducing the water flows in the canals may reduce seepage and effects on groundwater tables.

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Notes

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Synopsis of water management experiments in Indonesia

A. Gani, A. Rahman, Dahono, Rustam, and H. Hengsdijk

As the demand for industrial, municipal, and other water uses increases, less water will be available for Indonesian agriculture. To maintain food security, means must be developed to increase the productivity of water used in agriculture.

This paper describes the results of three field experiments in a recently reclaimed lowland rice area of Riau Province assessing the effects of different water management practices (continuously flooded and intermittent wetting and drying), seedling age, and nutrient management. Regularly, the number of (effective) tillers, plant height, leaf area, and biomass distribution over plant parts were measured during growth.

Because the experiments were severely damaged by rats from 90 to 110 d after transplanting (DAT), here results are reported of only plant characteristics measured before 90 DAT. Intermittent irrigation consistently performed better than continuously flooded irrigation, that is, it produced more (effective) tillers, leaf area, and biomass. Seedlings of 7 and 14 d had more vigorous vegetative plant growth than 21-d-old seedlings—they produced more (effective) tillers and biomass, taller plants, and longer roots. But the positive effect of younger seedlings on leaf area was not shown under flooded conditions. Organic manure applied at 3 t ha^{-1} showed positive effects on biomass production compared with 0 and 6 t ha^{-1}. However, the effect of organic manure at 90 DAT was determined only in combination with a high fertilizer application. A crop receiving 1 t lime and 90 kg N-P_2O_5-K_2O ha^{-1}, of which 50% was given at 7 and 28 DAT, respectively, performed better than a crop receiving 1 t lime and 4 t manure ha^{-1}.

Water is an important production factor in lowland rice systems. Concern about water scarcity is rising in Indonesia. Prolonged dry periods in 1991, 1994, and 1997 raised concern about the sustainability of "conventional" flooded rice systems. In addition, as the demand for industrial, municipal, and other water uses increases, less water will be available for agriculture. To maintain food security, the productivity of water used in agriculture must be increased.

Preliminary water management experiments in Sukamandi showed that different drainage treatments produced significantly higher yields than flooded rice (BALITPA 1999). Other publications also indicate water savings in rice production without a yield reduction (Yamazki and Harada 1982, IRRI 1995, Bhuiyan et al 1996). At the same time, the System of Rice Intensification (SRI) was developed, which consists of a set of agronomic practices with apparent synergistic effects (Uphoff 1999). Besides intermittent drying and flooding of rice fields, SRI consists of the use of young seedlings (8–15 d old), transplanting with wide spacing (at least 25 × 25 cm), the addition of organic matter to supply micronutrients, and frequent weeding to aerate the soil. In Madagascar, for example, this set of practices resulted in a considerable increase in rice yields together with water savings compared with the conventional rice systems (Uphoff 2001).

In newly opened irrigated lowland in Nagedang (Riau Province), rice yields are extremely low (0.3 t ha^{-1}) because of the high iron content in the soil (90–111 mg Fe 100 g^{-1} soil). In Fe-toxic lowland soils of Sitiung, West Sumatra, intermittent drainage and NPK fertilizer application produced average yields of 4–5 t ha^{-1} (CRIFC 1995).

This paper describes three experiments on Fe-toxic soils of Riau Province assessing different SRI components under continuously flooded and alternate wetting-and-drying conditions.

Objective of experiments

The experiments aim at evaluating and understanding the performance of rice systems under continuously flooded and intermittent wetting-and-drying conditions in Fe-toxic soils. The specific goals of the experiments are to assess the effects of reduced water input on rice growth and yield together with the effects of (1) seedling age, (2) organic matter amendments, and (3) nutrient management.

Materials and methods

Three on-farm field experiments were conducted in the recently reclaimed lowlands of Riau Province from July to November 2001. In all experiments, pests were controlled using local recommendations. Weeding was by hand while weed biomass was removed from the fields.

Experiment 1

Experiment 1 aimed at evaluating the effects of different water management practices (flooding and intermittent irrigation) and seedling age (21, 14, and 7 d old) on the growth and yield of rice. The experiment was designed as a split plot with four replications, with water management as the main plot and seedling age as the subplot. In intermittent irrigation, fields were flooded for 1 d and then drained for 6 to 8 d before the next irrigation. After 40 days after transplanting (DAT), draining periods were shorter (4 to 6 d) because of the increased water requirements of the growing plant. Seedlings of 7, 14, and 21 d (variety IR36) were transplanted with 1 seedling per hill and 25 × 25-cm spacing.

Lime and manure (1 and 4 t ha^{-1}, respectively) were homogeneously incorporated during field preparation. NPK fertilizer was applied as a split dressing, with 45 kg N, 90 kg P_2O_5, and 45 kg K_2O ha^{-1} at field preparation and 45 kg N and 45 kg K_2O ha^{-1} before panicle initiation.

Within each 8 × 6.5-m^2 plot, two sections each of 1 m^2 were randomly allocated for destructive samplings at 55 and 90 DAT, which corresponded with panicle initiation and 50% flowering, respectively. Destructive sampling was used to determine biomass (in root and shoot) and leaf area (using the length by width method).

Six randomly selected hills were selected to determine plant height and the number of (effective) tillers at 10-d intervals.

Experiment 2

In experiment 2, the effects of different water management (flooded and intermittent irrigation), organic matter amendments (0, 3, and 6 t manure ha^{-1}), and fertilizer (two NPK levels) on rice growth and yield were determined. Water treatments were as described in experiment 1. Manure was applied according to the treatments during field preparation together with 1 t lime ha^{-1}, which all treatments received. Fertilizer levels were low (75-50-50 kg N-P_2O_5-K_2O ha^{-1}) or high (150-100-100 kg N-P_2O_5-K_2O ha^{-1}). The experiment was designed as a split-split-plot with three replications, with water management as the main plot, organic matter as the subplot, and fertilizer level as the sub-subplot.

Rice seedlings (variety IR36) of 21 d were transplanted at 2 seedlings $hill^{-1}$ and 25 × 25-cm spacing.

Within each 8 × 6.5-m^2 plot, two sections each of 1 m^2 were randomly allocated for destructive samplings at 53 and 90 DAT. Destructive and nondestructive measurements were as described under experiment 1.

Experiment 3

Field experiment 3 aimed at assessing different nutrient management practices under different water management (flooded and intermittent irrigation). The following treatments were applied:

F0: Control, without lime, manure, and fertilizer
F1: 1 t lime ha^{-1} and 4 t manure ha^{-1}
F2: 1 t lime ha^{-1} and 90-90-90 kg N-P_2O_5-K_2O ha^{-1}, with 50% at 7 and 28 DAT

F3: 1 t lime ha^{-1} and 90-90-90 kg N-P_2O_5-K_2O ha^{-1}, with 50% at 28 and 49 DAT

F4: 1 t lime ha^{-1} and 90-90-90 kg N-P_2O_5-K_2O ha^{-1}, with 33% at 7, 28, and 49 DAT

Experiment 3 was a split-plot design with three replications, with water management as the main plot and nutrient management as the subplot. Seedlings of 15 d (variety IR36) were transplanted with 1 seedling $hill^{-1}$ and 25 × 25-cm spacing, in 5 × 4.5-m^2 plots.

Destructive sampling took place at 90 DAT and measurements were as described in experiment 1. Nondestructive measurements were similar to those described under experiment 1 but at 15-d intervals.

Results

Since the experiments were severely damaged by rats from 90 to 110 DAT, the results are shown of only plant characteristics measured before 90 DAT.

Effects of water management

The average crop characteristics measured at 90 DAT in the flooded and intermittent irrigation treatments of the three experiments are shown in Table 1.

Only in experiment 2 were significant differences in plant height observed between flooded and intermittent irrigation, that is, plants under intermittent irrigation are taller.

In all three experiments, plants under intermittent irrigation produced more tillers than flooded plants: 22%, 36%, and 32% more tillers in experiments 1, 2, and 3, respectively. The number of effective tillers showed the same trend (data not shown). In general, intermittent irrigation affected root dry matter and length positively in experiments 1 and 2.

In all three experiments, the leaf area of plants grown under intermittent irrigation tends to be larger than that of flooded plants, although differences are not always significant.

Differences in total dry matter production are significant in all experiments, that is, biomass production of plants in the intermittent treatment is on average 32%, 29%, and 26% higher than that of plants under the flooded treatments in experiments 1, 2, and 3, respectively.

Effects of seedling age

The average crop characteristics measured at 90 DAT of experiment 1 are shown in Table 2.

The plant height of young seedlings (7 and 14 d) tends to be greater than that of old seedlings (21 d) and they produce significantly more tillers: 21% and 22% more tillers in 7- and 14-d-old seedlings, respectively, than in 21-d-old seedlings. The number of effective tillers produced in 7- and 14-d-old seedlings was also higher at 90 DAT (data not shown).

Table 1. Crop characteristics in flooded and intermittent treatments of experiments 1, 2, and 3, 90 d after transplanting.

Characteristic	Experiment 1[a]	Experiment 2	Experiment 3
Plant height (cm)			
Flooding	71.1 a	72.6 a	74.2 a
Intermittent	82.2 a	84.8 b	79.5 a
No. of tillers hill^{-1}			
Flooding	33.4 a	28.3 a	26.7 a
Intermittent	40.6 b	38.4 b	35.2 b
Root dry matter (g hill^{-1})			
Flooding	7.2 a	3.3 a	–
Intermittent	9.2 b	4.9 b	–
Root length (cm)			
Flooding	27.5 a	25.4 a	–
Intermittent	32.5 b	31.6 a	–
Leaf area index			
Flooding	2.3 a	2.2 a	2.3 a
Intermittent	3.2 b	2.7 a	2.8 a
Total dry matter (g hill^{-1})			
Flooding	24.1 a	22.7 a	22.1 a
Intermittent	35.5 b	32.0 b	29.9 b

[a]Values with the same letter in a column for the same characteristic are not significantly different at 5% Tukey test.

Table 2. Crop characteristics of 7-, 14-, and 21-d-old seedlings in experiment 1, 90 d after transplanting (DAT).

Characteristic	DAT[a]		
	7	14	21
Plant height	76.9 ab	81.9 b	71.2 a
Number of tillers hill^{-1}	39.4 b	40.2 b	31.2 a
Leaf area index	3.0 ab	3.1 b	2.3 a
Root length (cm)	32.2 a	30.6 a	27.2 a
Root dry matter (g hill^{-1})	6.1 b	5.6 b	2.8 a
Shoot dry matter (g hill^{-1})	26.9 b	26.6 b	21.4 a

[a]Values with the same letter and in the same row are not significantly different at 5% Tukey test.

Young seedlings (7 and 14 d) tend to have a larger leaf area than 21-d-old seedlings. A similar trend in root length can be observed although none of the differences was significant.

The same tendencies for biomass production are shown: 7- and 14-d-old seedlings produced more biomass in roots and shoots than 21-d-old seedlings at 90 DAT.

The interaction between water management regime and seedling age in experiment 1 was significant: the positive effect of young seedlings on leaf area did not show up under flooded conditions, whereas, in the intermittent water treatment, seedlings of 7 and 14 d produced significantly more leaf area than 21-d-old seedlings (Table 3).

Effects of organic matter amendment

The average crop characteristics measured at 90 DAT of experiment 2 for the three organic matter amendments are shown in Table 4.

The effects of organic matter application on many crop characteristics are not ambiguous. Crops perform better with 3 t manure ha^{-1} than with 0 or 6 t manure ha^{-1}. Total biomass is highest in the treatment with 3 t manure ha^{-1}, whereas the biomass production of 0 and 6 t manure ha^{-1} is not different from each other. How-

Table 3. Leaf area index of seedlings with different age (7, 14, and 21 d) 90 d after transplanting under flooding and intermittent conditions.

Seedling age (d)	Flooding[a]	Intermittent
7	2.2 a	3.6 b
14	2.3 a	3.7 b
21	2.5 a	2.4 a

[a]Values with the same letter in the same column are not significantly different at 5% Tukey test.

Table 4. Average crop characteristics at 90 d after transplanting in experiment 2 using different amounts of organic matter amendments (0, 3, and 6 t ha^{-1}) and two fertilizer levels.

Characteristic	Organic matter amendment[a] (t ha^{-1})		
	0	3	6
Plant height (cm)	74.3 a	83.4 b	78.3 ab
Number of tillers $hill^{-1}$	35.0 b	34.7 b	30.3 a
Root dry matter (g $hill^{-1}$)	4.7 b	4.3 b	3.2 a
Shoot dry matter (g $hill^{-1}$)	21.9 a	26.1 b	21.8 a
Leaf area (cm^2 $hill^{-1}$)	1,466 a	1,619 a	1,531 a
Root length (cm)	31.0 a	30.9 a	32.7 a

[a]Values with the same letter and in the same row are not significantly different at 5% Tukey test.

ever, an interaction effect existed between organic matter and fertilizer application—the organic matter application showed an effect on total dry matter production only in the high fertilizer application (Table 5).

Effects of nutrient management

The average crop characteristics for the different nutrient management treatments in experiment 3 measured at 90 DAT are shown in Table 6.

Almost all crop characteristics of the control treatment (F0) are significantly different from those of the other treatments. Fertilizer application at 7 and 28 DAT (F2 treatment) results in the tallest plants and highest number of tillers, leaf area index, and dry matter production although the differences with F3 (fertilizer application at 28 and 49 DAT) and F4 (fertilizer application at 7, 28, and 49 DAT) are significant only for plant height.

Table 5. Biomass production in experiment 2 with different amounts of organic matter amendments in two fertilizer treatments at 90 d after transplanting.

Organic matter amendment ($t\ ha^{-1}$)	Total dry matter production[a] ($g\ hill^{-1}$)	
	Low NPK	High NPK
0	22.9 a	30.1 b
3	24.5 a	35.6 c
6	23.9 a	27.3 ab

[a]Values with the same letter and in the same column are not significantly different at 5% Tukey test.

Table 6. Crop characteristics in different nutrient management treatments (see text for explanation) of experiment 3 at 90 d after transplanting.

Characteristic	F0[a]	F1	F2	F3	F4
Plant height (cm)	45.5 a	69.6 b	107.4 c	79.8 b	82.0 b
Number of tillers $hill^{-1}$	18.3 a	27.0 b	37.8 c	35.8 c	35.8 c
Leaf area index	1.70 a	2.44 ab	2.95 b	2.8 b	2.8 b
Shoot dry matter ($g\ hill^{-1}$)	10.6 a	20.9 b	29.0 c	25.5 bc	25.1 bc

[a]Values with the same letter and in the same row are not significantly different at 5% Tukey test.

Conclusions and discussion

The major conclusions based on the results of these experiments are as follows:

1. Intermittent irrigation had consistently positive effects on rice plants in Fe-toxic soils of Riau Province in terms of the number of (effective) tillers, root growth, leaf area development, and biomass production up to 90 DAT. Unfortunately, grain yields could not be determined since the crops were severely damaged by rats before harvesting. Yields would probably have been higher under intermittent irrigation because of the higher biomass, leaf area index, and number of effective tillers at 90 DAT. Also, other literature sources describe the beneficial effect of aerobic soil conditions during (parts of) the growing season on rice growth and production in Fe-toxic soils (Van Mensvoort et al 1985, Vizier et al 1990).

   We did not measure the exact amount of water used in the intermittent irrigation, but the amount of water applied was considerably less than in conventionally flooded treatments. However, we were not able to create completely drained soil conditions at all times in the intermittent irrigation treatments since seepage from adjacent flooded fields interfered. As a result, plants may have grown regularly under saturated soil conditions, more than the water management protocol prescribed.
2. Young seedlings (7 or 14 d old) performed better than 21-d-old seedlings. The plants of young seedlings were taller and they produced longer and heavier roots and more (effective) tillers and biomass. The positive effect of younger seedlings on leaf area was not shown under flooded conditions.
3. Organic matter incorporated at 3 t manure ha^{-1} increased plant height and root length at 90 DAT compared with 0 and 6 t manure ha^{-1}. However, the effect of organic matter on biomass production at 90 DAT was different under different fertilizer regimes. In this study, the application of 6 t organic matter ha^{-1} did not result in an additional yield effect compared with 3 t organic matter ha^{-1}, perhaps because of the already high soil organic matter content (2.41–6.67%). Both Diekmann et al (1992) and Abe et al (1995) showed that organic matter amendments may suppress the growth of rice plants because of the toxic decomposition products of organic matter.
4. Increasing NPK fertilization from 75-50-50 to 150-100-100 kg $N-P_2O_5-K_2O$ ha^{-1} increased plant height, the number of (effective) tillers, and leaf area. Root length was not affected. Furthermore, the effects of nutrient management were different between flooded and intermittent conditions. Yamazaki and Harada (1982) reported that a high nitrogen supply suppresses crown-root elongation, resulting in small root systems. Here, high fertilizer rates increased root production, but not to deep soil layers.

A crop receiving 1 t lime and 90 kg N-P_2O_5-K_2O ha^{-1} given 50% at 7 and 28 DAT, respectively, performed better than a crop receiving 1 t lime and 4 t manure ha^{-1}. Crops receiving fertilizer at different moments during the growing season tended to perform worse, but differences were often not significant.

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Notes

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Biophysical and economic implications of integrated crop and resource management for rice in Indonesia

I.P. Wardana, P.S. Bindraban, A. Gani, A.K. Makarim, and Irsal Las

Rice production in Indonesia faces several problems simultaneously: water shortage, declining productivity, and environmental pollution. To cope with these problems, the Ministry of Agriculture promotes integrated crop and resource management (ICM) for rice. On-farm research and assessment are carried out in eight case-study areas throughout the country. One group of farmers applies ICM and another group conventional practices. Three ICM components are tested: improved nutrient management, planting of young single seedlings, and the application of intermittent irrigation. The biophysical and economic implications of the introduction of ICM for farm households are presented in this paper. Farmers applying all three ICM components obtained the highest average yield of 6.9 t ha^{-1}, whereas conventional farmers attained on average 5.4 t ha^{-1}. Variables that significantly affected yield were organic matter, irrigation method, and the interaction of P fertilization with irrigation method. Farmers using three ICM components need additional labor of 15 d ha^{-1}, mainly for organic matter and split fertilizer application, weeding, and irrigation. Net returns of ICM farmers using three components are 37% higher than those of conventional farmers, despite 16% higher costs. The relatively low number of ICM farmers using intermittent irrigation is thought to have been caused by a lack of skill and cooperation among farmers and irrigation engineers and should get proper attention in the future on-farm development of ICM.

Irrigation water is an important production factor in rice systems but is no longer available unlimited in rice-growing areas (Bindraban 2001), as in Indonesia. In some areas, water shortages have already caused crop failure. A large portion of irrigation water is lost because of inefficiency in distribution, evaporation, seepage, and percolation. Agronomic practices are not available now to systematically save water in rice production.

Since 1997, rice production has decreased in Indonesia and rice productivity has declined in intensively cropped rice systems (e.g., Cassman 2001). Consequently, rice farmers do not produce enough income to meet their needs. In some provinces, farmers have already shifted to more profitable crops such as tobacco, sugarcane, and citrus. In addition, rice production is associated with high fertilizer and biocide use, causing the emission of nitrate and biocide compounds, respectively. To cope with these problems, integrated crop and resource management (ICM) has been proposed to reverse the declining trend in rice productivity, increase farmers' income, and improve resource use to achieve sustainability.

ICM is a combination of water, plant, and nutrient management that exploits synergistic interactions and aims at improved resource use, that is, higher productivity of water, land, and labor (Kartaatmadja and Fagi 2000). Over the past two years, field experiments during four seasons at the Research Institute for Rice showed that ICM increased rice yields from 6.2 to 8.4 t ha^{-1} (Kadir et al 2001). On the basis of these results, the Agency for Agricultural Research and Development in Indonesia started to promote ICM to farmers. In the dry season of 2001, an ICM project began, aimed at the on-farm assessment of ICM in eight provinces of Indonesia (Gani 2001). The objective of this paper is to analyze the biophysical effectiveness of the agronomic measures introduced through ICM and the effects of these measures on farm economics. We touch upon some factors that may affect the adaptability of the ICM measures.

Materials and methods

ICM

Based on the findings in field experiments, three promising ICM practices were identified to be tested on-farm. First, through intermittent irrigation, rice fields are alternately flooded and drained depending on the prevailing rainfall and soil water status. It is assumed that this water management practice will improve soil aeration. Three days after transplanting, when the soil starts to crack, irrigation water is applied till the soil is saturated. Then, irrigation water is not applied for 5 to 6 d, after which a new irrigation starts till soil saturation. This water management is maintained throughout the vegetative phase. From panicle initiation to 25 d before harvest, the field is flooded with a thin water layer. Second, young single seedlings of only 10–15 d are planted at 1 seedling $hill^{-1}$ at a spacing of at least 20×20 cm. This practice is introduced because young seedlings tend to produce more roots and tillers (Uphoff 2001). Third, fertilizer management consists of organic matter application—compost, farmyard manure, or rice straw is incorporated during land preparation (2–4 t ha^{-1}) and nitrogen application is based on leaf color chart (LCC) monitoring. The LCC consists of six color shades ranging from light yellow green (no. 1) to dark green (no. 6). The first amount of N fertilizer (90 kg urea ha^{-1}) is applied 15–20 d after planting. A second and third N fertilizer application (each 70 kg urea ha^{-1}) are made only when the LCC reading is below no. 4. The leaf color is monitored weekly till panicle initiation. Soil P and K monitoring are done before transplanting to fine-tune the amount of P and K fertilizer applied.

Location

ICM practices have been introduced in various provinces in Indonesia. A participatory appraisal involving agricultural scientists, extension workers, and farmers was carried out to identify appropriate ICM practices. An on-farm assessment of ICM was made in North Sumatra, West Sumatra, West Java, Central Java, East Java, Bali, West Nusatenggara, and South Sulawesi, where, at each location, a case-study area of 5.0 ha was available. One group of farmers applied ICM practices, whereas another group continued with conventional practices. The management of both groups, that is, material and labor inputs and yield, was recorded. Farmers did not always adopt the entire ICM packages, but instead adopted various combinations of ICM components.

Data analysis

Results from four provinces (West Java, Central Java, West Nusatenggara, and South Sulawesi) are presented because of the availability of data from those sites only. Table 1 presents the soil characteristics from the sites. First, input and output variables were used to estimate the contribution of the various agronomic practices introduced to yield. Especially in empirical studies, such as ours, predictor variables are correlated and, frequently, several regression models give similar results. However, with many predictor variables, alternative models are easily overlooked. To overcome this problem, the GenStat procedure RSELECT (Goedhart and Thissen 2001, GenStat 2000) is used, which evaluates all possible models with one, two, or more predictor variables. Identification of the best model depends on well-known criteria such as R^2 (Montgomery and Peck 1992).

Table 1. Soil characteristics of six case-study sites where ICM was assessed on-farm.

Location	West Java		Central Java		West Nusatenggara,	South Sulawesi,
	Subang	Garut	Grobogan	Sragen	Lombar	Maros
pH H_2O	5.9	6.9	7.1	5.7	5.4	6.4
pH KCl	5.2	6.1	6.5	5.1	4.5	5.1
C (%)	1.99	2.02	2.01	1.38	2.27	1.81
N (%)	0.20	0.10	0.06	0.07	0.10	0.23
P_2O_5-HCl (mg 100 g^{-1})	0.3[a]	45.7	74.8	55.9	25.7	39.0
K_2O HCl (mg 100 g^{-1})	48.7	23.0	11.0	6.2	13.0	0.2[b]
Zn (ppm)	8.29	6.57	0.59	3.16	6.87	–
Fe (ppm)	188.8	18.7	9.4	41.2	174.0	–
Mg (mg 100 g^{-1})	8.6	5.12	1.76	2.22	1.09	–
Ca (mg 100 g^{-1})	23.83	7.52	26.48	6.59	10.54	–
Na (mg 100 g^{-1})	1.60	1.66	0.34	0.11	0.13	1.05

[a] = in ppm. [b] = in mg 100 mg^{-1}.

Second, inputs and outputs from 72 farmers of the four sites were analyzed using partial budget and cost-benefit analysis (Kay and Edwards 1994).

Results

The results will be presented in two separate sections. The first section deals with the contribution of the biophysical factors underlying ICM practices to yield. The second section analyzes the profitability of the introduced practices.

Biophysical analysis

Of the total of 72 farmers monitored, 39 farmers adopted one or more ICM components and 33 applied conventional management practices. Among the 39 ICM farmers, 10 farmers adopted one component (organic matter application), 17 adopted two components (organic matter application and young single seedlings), and 12 adopted three components (organic matter application, young single seedlings, and intermittent irrigation). To enable a comparison between ICM components and conventional practices, the 72 farmers were divided according to the number of SRI components adopted. Any differences between farmers because of soils, skills, etc., were neglected. Rice yields of ICM farmers were significantly higher than those of conventional farmers (Table 2). Conventional farmers attained on average 5.4 t ha^{-1}, whereas ICM farmers obtained 5.8, 6.1, and 6.9 t ha^{-1} adopting one, two, and three components, respec-

Table 2. Outputs and inputs used by conventional and ICM farmers. ICM components applied shown in boldface: F = flooded, I = intermittent irrigation, 20-3 = seedling age and number of seedlings $hill^{-1}$, OM = organic matter, N = nitrogen fertilizer application based on the leaf color chart.

	Conventional		ICM	
Outputs/inputs	(F/20-3) n = 33	(F/20-3/ **N**/**OM**) n = 10	F/**16-1**/ (**N**/**OM**) n = 17	(**I**/**16-1**/ **N**/**OM**) n = 12
Yield (kg ha^{-1})	5,401	5,813	6,068	6,889
Organic matter (kg ha^{-1})	0	1,880	2,253	2,923
Age of seedlings (d)	24	22	14	15
Nitrogen, urea (kg ha^{-1})	330	220	249	224
Phosphate, SP36 (kg ha^{-1})	62	29	37	42
Potassium, KCl (kg ha^{-1})	19	2	0	44
Biocide (L ha^{-1})	0.6	1.0	0.7 ns[b]	1.1
Weeding[a]	0	1	1	1
Fertilizer split[a]	0	1	1	1
Irrigation method[a]	0	0	0	1

[a]Weeding, split fertilizer application, and irrigation method are proxy variables derived from labor input. [b]ns = not significant. Other values of ICM are significant at α = 5% relative to conventional practices.

tively. Farmers using one or more ICM components realized on average 13% higher yields than conventional farmers.

ICM farmers applied significantly less urea and phosphate (SP36) than conventional farmers did. However, they used organic matter instead. Farmers using three ICM components used more potassium (KCl) and biocides than conventional farmers.

The first step in the statistical analysis involved the definition of proxy variables for weeding, split fertilizer application, and irrigation method. These operations are considered key variables in ICM and require, in general, more labor than in conventional practices. For example, farmers using split fertilizer application as in ICM need more labor to monitor the LCC for possible required fertilizer applications. Labor is an important factor in economic analyses, but it does not affect yield per se. The agronomic changes resulting from labor activities, such as weeding, cause changes in crop performance. Hence, proxy variables for weeding, split fertilizer application, and irrigation method are derived from average labor inputs.

The second step was the identification of predictor variables. RSELECT identified the best model, consisting of four predictor variables—organic matter, irrigation method, phosphate, and split fertilizer application based on their t-values (>2.0). Other nonsignificant variables, such as urea, KCl, biocide, age of seedling, and weeding, were excluded from further analysis.

Subsequently, all two-way interactions between significant variables were analyzed. Only the interaction between irrigation method and phosphate was significant (P <0.05). Hence, the best-fitted equation to estimate yield is

$$y = 5{,}592 - 141\, x_1 - 2.4\, x_2 + 0.3\, x_3 + 2{,}060\, x_4 - 32.7\, x_2x_4 \qquad (R^2 = 51)$$

in which x_1 = split fertilizer application (1 = yes, 0 = no), x_2 = phosphate (kg ha^{-1}), x_3 = organic matter (kg ha^{-1}), x_4 = irrigation method (1 = intermittent, 0 = flooded), and x_2x_4 = interaction between phosphate and irrigation method. The explained variance is 51%. The effects of split fertilizer application and the two-way interaction were partly confounded.

Organic matter application has a positive effect on yield—an approximately 300-kg increase in yield per ton of applied organic matter under both intermittent irrigation and flooding conditions. The equation suggests that changing water management from flooding to intermittent irrigation adds approximately 2 t ha^{-1} to yield. There is a small negative interaction between phosphate and irrigation method, that is, under flooding, yield decreases ± 24 kg ha^{-1} per 10 kg phosphate ha^{-1} applied. Under intermittent irrigation, however, yield decreases ± 350 kg ha^{-1} when 10 kg phosphate ha^{-1} is applied.

Yields estimated by applying the equation are compared to observed yield (Fig. 1). Most farmers realizing low yields in general use old seedlings (more than 25 d old) and no organic matter and practice flooded irrigation. In addition, these farmers face higher pest incidence (rats) than other farmers (data not shown). Farmers attain-

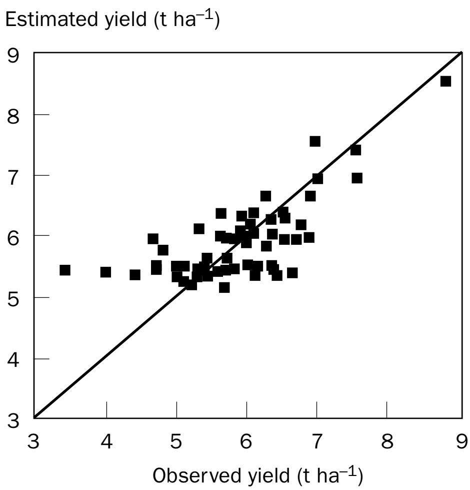

Fig. 1. Relationship between observed and estimated yields of rice.

Table 3. Labor used by conventional and ICM farmers for different operations. See Table 2 for explanation of codes.

Labor inputs (d ha^{-1})	Conventional		ICM	
	(F/20-3) n = 33	(F/20-3 /N/OM) n = 10	(F/16-1/ N/OM) n = 17	(I/16-1/ N/OM) n = 12
Seedbed	5.8	6.6 ns[a]	4.9 ns	5.1 ns
Land preparation	26.6	28.1 ns	23.3	24.4
Organic matter application	0.0	6.0	6.1	5.9
Planting	16.1	14.0	19.7	16.1 ns
Weeding	18.0	25.7	25.7	25.1
Fertilizer application	7.3	11.5	11.0	11.2
Irrigation	8.3	4.5	6.9	11.0
Spraying	4.1	5.1 ns	3.3 ns	5.3 ns
Postharvest	41.9	41.0 ns	36.7	38.8 ns
Total	128.0	142.4	137.6	142.9

[a]ns = not significant. Other values of ICM are significant at α = 5% relative to conventional practices.

ing high yields use young seedlings (15 d old) and organic matter (4 t ha^{-1}) and apply intermittent irrigation.

Economic analysis

In this section, the economic variables of the introduced agronomic practices are presented. Total labor requirements for ICM farmers are significantly higher than those of conventional farmers (Table 3). Additional labor needed for ICM ranges from 10 to

15 d ha^{-1}. ICM farmers using three components need additional labor of 15 d ha^{-1}, mainly for organic matter application, weeding, split fertilizer application, and irrigation.

A partial budget analysis was carried out to estimate additional returns (Table 4). The level and costs of unchanged inputs are not included. The total additional returns of ICM farmers are US$21, $55, and $110 for one, two, and three ICM components, respectively. The production factors of ICM farmers that reduced costs are N fertilizer (urea), seed, and phosphate. Factors that increased costs are organic matter, biocides (herbicides, fungicides, and insecticides), and additional labor for organic matter incorporation, weeding, and split fertilizer application.

Cost-benefit analysis shows that total costs (material and labor costs) of ICM farmers are higher than those of conventional farmers (Table 5). However, the share of labor (70%) and material costs (30%) is similar for ICM and conventional farmers. Net returns of ICM farmers using three components are 37% higher than those of

Table 4. Partial budget analysis of ICM farmers compared to conventional rice cultivation. See Table 2 for explanation of codes.

ICM practices/ output/input	F/20-3/N/OM		F/16-1/N/OM		I/16-1/N/OM	
	Amount	Value (US$)	Amount	Value (US$)	Amount	Value (US$)
Added return						
Increasing yield (kg ha^{-1})	411.7	40.76	667.3	66.06	1,487.7	147.28
Reduced cost						
Seed savings (kg ha^{-1})	6.4	1.73	27.2	7.34	25.5	6.89
Urea (kg ha^{-1})	109.8	12.85	80.9	9.47	105.6	12.36
SP36 (kg ha^{-1})	32.9	5.23	25.1	3.99	19.7	3.13
KCl (kg ha^{-1})	17.2	3.44	18.7	3.74	25.2	–5.04
Labor (d ha^{-1})	4.3	5.59	8.7	11.32	4.7	6.15
Land preparation and planting labor						
Subtotal		69.59		101.92		170.76
Added cost						
Organic matter application labor (d ha^{-1})	6.0	7.80	6.1	7.93	5.9	7.67
Weeding labor (d ha^{-1})	7.7	10.01	7.7	10.01	7.1	9.23
Fertilizer application labor (d ha^{-1})	4.2	5.46	3.7	4.81	3.9	5.07
Organic matter (kg ha^{-1})	1,880	17.86	2,253	21.40	2,923	27.77
Biocide (L ha^{-1})	0.4	6.00	0.1	1.50	0.5	7.50
Irrigation labor (d ha^{-1})	0.8	1.04	0.8	1.05	2.7	3.55
Subtotal		48.17		46.70		60.79
Change (A + B) – C		21.42		55.22		109.98

Wage rate = US$1.31 per day.

Table 5. Cost-benefit analysis and some economic indicators of ICM practices compared with conventional practices. See Table 2 for explanation of codes.

Return/cost/economic indicator	Conventional		ICM practices					
	S/20-3		S/20-3/N/OM		S/16-1/N/OM		I/16-1/N/OM	
	Value	%	Value	%	Value	%	Value	%
Return (US$ ha^{-1})	534.71	100	575.47	100	600.77	100	681.99	100
Material costs (US$ ha^{-1})	72.21	30	72.82	28	70.57	28	90.15	33
Labor costs (US$ ha^{-1})	166.40	70	185.12	72	178.88	72	185.77	67
Total costs (US$ ha^{-1})	238.61		257.94		249.45		275.92	
Net return (US$ ha^{-1})	296.10	100	317.52	107	351.32	118	406.07	137
Breakeven yield (t ha^{-1})	2.4		2.6		2.5		2.8	
Return to labor (US$ d^{-1})	41.8	100	40.4	97	43.7	105	47.7	114
Return-to-cost ratio (R/C)	2.24		2.23		2.41		2.47	

conventional farmers, although total costs are 16% higher (Table 5). Hence, the return to labor of ICM farmers using three components is 14% higher than that of conventional farmers. This indicates that ICM farmers are able to increase their daily income from $4.20 to $4.80. The breakeven yield of ICM farmers is higher than that of conventional farmers since the total cost incurred in rice production is higher. Also, the overall return-to-cost ratio of ICM farmers is higher (Table 5).

Discussion and conclusions

Intermittent irrigation has a strong positive effect on yield. Various reasons have been mentioned in the literature that could explain this observation. Drew (1997), for instance, shows that root growth under aerobic conditions is better than under anaerobic conditions. Alternation of wetting and drying of the field improves oxygen concentration in the root zone. Biological nitrogen fixation (BNF) is also facilitated under aerobic conditions and contributes to the conversion of nitrogen into forms available for uptake by the rice plant (Baldani et al 1997). In this study, however, no observations were made on BNF. The high iron concentration of the soils (Table 1) may also partly explain the yield increase because of intermittent irrigation, as iron toxicity suppresses yield under flooded conditions (Ponnamperuma 1985).

Organic matter application improves yield perhaps because it supplies nutrients more steadily during the growing season even if the total amount of nutrients is less compared with fertilizer application (Uphoff 2002). ICM farmers that apply high amounts of organic matter use less urea, which indicates that urea is replaced by organic matter (Table 2).

The interaction of phosphate with flooded irrigation shows a slight negative effect on yield (Fig. 2), perhaps because the soil phosphate contents of farmers' fields were relatively high (Table 1). Under intermittent irrigation, the effect was stronger,

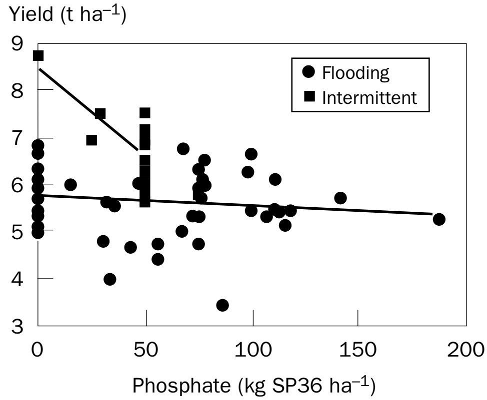

Fig. 2. Relationship between the application of phosphate and yield of rice under flooded and intermittent irrigation.

but this may be an artifact because of an outlier in the low number of data points (Fig. 2).

Seedling age and number of plants per hill do not affect yield, despite positive results found in experimental fields (Kadir et al 2001, Uphoff 2001). However, inconclusive results have also been found in various field experiments (Arafah et al 2001, Diratmaja et al 2001, Pramono et al 2001, Sembiring and Djaswadi 2001).

Net returns of ICM farmers are higher than those of conventional farmers. Despite higher returns, conventional farmers are reluctant to apply organic matter because of its limited availability and problems with its distribution in the field.

Higher yields of ICM farmers are associated with increased labor requirements, which can only be met as long as the return to labor in rice production is higher than for other labor opportunities. Labor savings may be feasible by replacing manual weeding with mechanical weeding and by incorporating organic matter using mechanical implements during land preparation.

The relatively low number of ICM farmers using intermittent irrigation could have been caused by the lack of skill and communication between irrigation engineers and farmers. In addition, the current irrigation infrastructure and farm management may hamper the rapid adoption of intermittent irrigation.

The promising biophysical and economic results that emerge from the introduction of ICM practices warrant a widening of the testing regions, a strengthening of the research efforts, and an initiation of analyses on institutional requirements to improve communication between engineers and farmers.

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Notes

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Water use of alternately submerged and nonsubmerged irrigated lowland rice

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The availability of freshwater for agriculture is declining in many parts of Asia, thus affecting lowland rice production. One water-saving management option in irrigated lowland rice systems is to reduce the amount of irrigation water per rice cropping season. Although farmers traditionally aim at having continuously flooded fields, water-saving techniques are receiving more and more attention.

One water-saving technique is to keep the field alternately submerged and nonsubmerged (ASNS). Field experiments were conducted at sites in irrigated lowland areas in China (Hubei) and the Philippines (Nueva Ecija) to compare two water regimes: (1) continuously submerged (CS) and (2) alternately submerged and nonsubmerged (ASNS). In ASNS regimes, fields were irrigated after at least 3 days without ponded water (up to 12 days just before panicle initiation). Nitrogen treatments were 180 kg ha^{-1} applied in various splits and no N fertilizer (control).

Savings in irrigation water in the ASNS treatments were 53–87 mm (13–16%) compared with the CS regime. Rice grain yields ranged from 7.2 to 8.7 t ha^{-1} and were not significantly affected by the water regimes. Water productivity was 0.91–1.48 kg grain m^{-3} water applied. In two out of three experiments, water productivity was significantly higher in the ASNS regime than in the CS regime.

The depth of the (perched) groundwater level was 0–30 cm below the soil surface in all experiments, thus minimizing the effect of aboveground water status on water availability for the rice plant. The soil moisture potential at PhilRice was never below –20 kPa. The experiments were conducted in extremely poorly drained, heavy-textured soils with a low seepage and percolation rate (max. 3.9 mm d^{-1} in the CS regime). The evaluation of ASNS regimes was based on soil texture, the formation of cracks that can cause bypass flow, and groundwater depth. These criteria were identified as the most relevant for recommendations on water management of water-saving regimes for lowland rice production.

In Asia, the availability of freshwater for agriculture is declining (Postel 1997) while demand for rice will increase because of population growth (Pingali et al 1997). Rice is a heavy consumer of freshwater and approximately 50% of the freshwater used in Asian agriculture is used for rice production (Guerra et al 1998). Because substantial expansion of the area planted to rice is unlikely, future production gains will have to come mainly from yield increases. Facing the increasing demand for food combined with the increasing scarcity of water, rice producers in Asia need to produce more rice with less water (Guerra et al 1998).

Growing awareness of the water scarcity has led to the formulation of water-saving technologies in rice production (Tabbal et al 1992, Wu 1999). One of these technologies is keeping the field alternately submerged and nonsubmerged, instead of keeping the field continuously submerged, what most farmers in Asia still practice.

Some studies indicated that an alternately submerged and nonsubmerged (ASNS) regime (also named "intermittent irrigation" or "alternately wet and dry") did not affect grain yield (Choudhury et al 1991, De Dios et al 2000) or even led to an increase in yield if irrigation was carefully managed (Wu 1999, Mao et al 2000). This yield benefit has been ascribed to better root vigor and depth (Mao et al 2000); a reduction in lodging, pests, and diseases (Yi 1999); and better soil oxygenation (Wang 1999). Cheng (1983) reported that aerobic soil conditions favored the removal of toxic chemicals in the rhizosphere. Other studies reported a yield decline when ASNS regimes were tested (Borell et al 1997, Lu et al 2000, Bouman and Tuong 2001).

To find explanations for this discrepancy in reported results, a new set of experiments was conducted to study water use and hydrology in irrigated rice under ASNS regimes compared with continuous submergence (CS). The study aimed at analyzing the magnitude of water savings and their effects on rice grain yield and water-use efficiency at two different N fertilization rates (zero and 180 kg ha^{-1}).

Materials and methods

Experimental sites

Three field experiments in lowland areas were conducted in subtropical Southeast Asia. Two experiments were located in Tuanlin (30°52′N, 112°11′E), Hubei Province, China, at an altitude of 100 m and were conducted during the summer season (April-September) of 1999 and 2000. A third field experiment was carried out at the Philippine Rice Research Institute (PhilRice) in Muñoz (15º40′N, 120º54′E), Nueva Ecija Province, Philippines, at an altitude of 40 m during the dry season (December-April) of 2000-01.

Table 1 gives the soil characteristics of the sites. Both sites have a heavy-textured soil and are located in irrigated lowland areas with nearby irrigation canals. The varieties used in Tuanlin were the hybrids 2You501 in 1999 and 2You725 in 2000. At PhilRice, the experiment was planted with the inbred variety IR72. Plots were regularly hand-weeded and pesticides were used to prevent insect and pest damage. No noticeable crop damage was observed in the three experiments.

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

Characteristic	Tuanlin	PhilRice
Texture	Clay loam	Silty clay
pH (H_2O) 1:1	6.5	5.4
Organic C (%)	1.03	1.77
CEC (cmol kg^{-1})	20.6	17.1
Available N (mg kg^{-1})	5.8	–
Total N (%)	–	0.14

Treatments

The experiments had a split-plot design with the water treatment as the main plot and the N treatments as subplots. Treatment combinations were replicated three times at Tuanlin in 1999 and four times at Tuanlin in 2000 and at PhilRice. At Tuanlin, results from water measurements in one replicate were not reliable and were therefore discarded from the analysis. In this replicate, seepage and percolation rates were fourfold compared with those of the same water regime in the other replicates. Plot sizes of subtreatments at Tuanlin were from 88 to 201 m^2, while at PhilRice all subtreatment plots were 84 m^2 (14×6 m).

The tested water treatments were alternately submerged and nonsubmerged (ASNS) and continuous submergence (CS). To prevent seepage between fields with different water regimes, plastic sheets were installed in the bunds to a depth of 40 cm below field level. This was well below the top of the hardpan. Water depth in both the CS and ASNS regimes was kept between 10 and 40 mm during the first 10 days after transplanting. After this 10-d period, the water level fluctuated between 10 and 100 mm in the CS regime. Maximum water depth in the ASNS regimes was 100 mm. During nonsubmerged periods of the ASNS regimes, the water level dropped below the field level. If from natural rainfall the water level exceeded a predetermined threshold of 100 mm, the plots were drained. In the ASNS regimes, the periods without standing water lasted for 3 to 5 days, except for the midseason drainage period just before panicle initiation, which lasted 10 days at Tuanlin.

Application rates of fertilizer N were 0 (not in Tuanlin in 1999) or 180 kg ha^{-1}. In Tuanlin in 1999 and 2000, the N treatment also involved the testing of three different timings of N application. Results of these timing experiments can be found in Cabangon et al (2001).

Measurements

At both sites, the amounts of irrigation, drainage, and rainfall were measured throughout the growing season. The discharge Q ($m^3\ s^{-1}$) in a 90° V-notch weir can be computed by the following equation:

$$Q = 1.34 \times h^{2.48}$$

where *h* is the water height in the weir in m (Kraatz and Mahajan 1975).

At PhilRice, the irrigation amount was determined using 90° V-notch weirs and 20 × 90-cm cutthroat flumes. From the water height at the inflow site, the discharge was determined by adopting reported values of discharge for the same size of cutthroat flume (Kraatz and Mahajan 1975). The amount of irrigation was calculated by integrating the discharge over each time-step between two readings of the water height in the weir and the flume.

Groundwater level was monitored at PhilRice with PVC pipes perforated 50 cm below field level. The surface water level was determined daily at both sites. At PhilRice, the water level below field level was not determined and tensiometers were installed at 10-cm depth to determine soil moisture potential in the water-saving treatments. Percolation rate at both sites was measured inside covered metal cylinders. Daily rainfall was taken from the weather station at both sites. Yield was measured from 4.8 m^2 at Tuanlin and 6 m^2 at PhilRice at harvest time.

Calculations and analyses

Water balance and weather data were analyzed for the period of transplanting to harvest. The cumulative crop evapotranspiration (ET_c) was estimated from the reference evapotranspiration, calculated from daily weather data according to the Penman-Monteith method and multiplied by crop factors for rice as described by Allen et al (1998). The crop factors for rice were based on continuously submerged conditions and therefore may overestimate ET_c for the ASNS regime. Total seepage and percolation were determined by subtracting total crop evapotranspiration from the summed water input by irrigation and rainfall minus any amount that was drained off ($SP = [I + R – D] – ET_c$). Grain yield data are presented at 14% moisture. Water productivity (kg grain m^{-3} water) was calculated as grain yield (kg ha^{-1}) divided by total water input (drainage water not subtracted) from rainfall and irrigation (m^3 ha^{-1}). For the 180 kg N ha^{-1} treatment, the average over two and four splits was taken since no statistical differences occurred among the splits. The IRRISTAT software package was used for the statistical analysis. The level of confidence was set at 95%.

Results

Crop duration and weather

Table 2 presents crop duration, average temperature, cumulative rainfall, crop evapotranspiration, and irradiation during the three experiments. The crop duration of the hybrid varieties grown at Tuanlin was on average 19 days longer than the inbred variety at PhilRice. Average daily ET_c was 4.4, 4.7, and 4.6 mm d^{-1} for Tuanlin in 1999, Tuanlin in 2000, and PhilRice, respectively. Average daily irradiation was 19.3, 20.0, and 20.2 MJ m^{-2} d^{-1} for Tuanlin in 1999, Tuanlin in 2000, and PhilRice, respectively. There was not much difference in average temperature, irradiation, and ET_c among the three experiments. Rainfall during the summer seasons of 1999 and 2000 at Tuanlin, however, was much higher than during the 2001 dry season at PhilRice. The average rainfall in Tuanlin in the same period of the year from 1989 to 1998 was

Table 2. Crop duration from transplanting to harvest (d), average temperature (°C), seasonal incoming radiation (MJ m^{-2} season^{-1}), evapotranspiration (ET_c, mm season^{-1}) and rainfall (mm season^{-1}), irrigation (mm season^{-1}), and seepage and percolation (mm season^{-1}) in Tuanlin in 1999 and 2000 and PhilRice in 2001.

Factors measuring weather and water balance	Tuanlin 1999	Tuanlin 2000	PhilRice 2001
Crop duration[a]	115	112	95
Av temperature	26.1	26.7	27.2
Σ irradiation	2,168	2,243	1,919
Σ ET_c	511	533	435
Σ rainfall	377	463	91
Σ irrigation in CS[b]	588	396	511
Σ irrigation in ASNS	501	343	427
Σ SP[c] in CS	454	327	168
Σ SP in ASNS	367	273	83

[a]Determined in plots that received 180 kg N ha^{-1}. [b]CS = continuously submerged, ASNS = alternately submerged and nonsubmerged. [c]SP = seepage and percolation.

546 mm; thus, 1999 and 2000 were relatively dry years. The dry season of 2001 at PhilRice was relatively wet because average rainfall at PhilRice in the same period of the year from 1990 to 2000 was 48 mm. The maximum diurnal precipitation was 65 mm at Tuanlin in 1999 on 26 June, 70 mm at Tuanlin in 2000 on 24 May, and 22 mm at PhilRice on 30 March 2001.

Yield

Table 3 presents the grain yields of the 0-N and 180-N treatments. The differences in grain yield between the water regimes were not statistically significant in any of the three experiments. Grain yields did strongly respond to N fertilization. The average increase in grain yield with 180 kg N ha^{-1} was 4.1 t ha^{-1} for Tuanlin in 2000 and 3.2 t ha^{-1} for PhilRice in 2001 compared with the control.

Water use and productivity

Table 2 presents the irrigation water inputs for the three experiments. Total water inputs, including rainfall, ranged from 965 mm season^{-1} for CS in Tuanlin in 1999 to only 518 mm season^{-1} for ASNS at PhilRice. Bouman (2001) reported typical values of 1,500–2,000 mm for lowland areas (including water used for land preparation). The water savings with ASNS were 13–16% compared with the conventional water management in the CS regime. However, irrigation water savings with ASNS were statistically significant only at PhilRice. In Tuanlin, irrigation water consumption was lower in 2000 than in 1999 because more rainfall occurred in 2000 (Table 2).

Table 3 Grain yield (t ha^{-1}) and water productivity (kg rice m^{-3} total water input) at Tuanlin in 1999 and 2000 and at PhilRice in 2001.

Site and water regime	Grain yield		Water productivity[a]
	0 N	180 N	180 N
Tuanlin 1999[b]			
CS[c]	–	8.6	0.91
ASNS	–	7.7	0.93
Tuanlin 2000			
CS	4.4	8.3	0.95
ASNS	4.5	8.7	1.09
PhilRice 2001			
CS	4.4	7.2	1.20
ASNS	4.1	7.6	1.48

[a]Average of 2 and 4 splits of 180 kg N ha^{-1}. [b]0 N was not carried out. [c]CS = continuously submerged, ASNS = alternately submerged and nonsubmerged.

Water productivity was 0.9–1.5 kg grain m^{-3} water input (see Table 3). Bouman and Tuong (2001) found typical water productivities of 0.3–1.1 kg grain m^{-3} water in the Philippines for CS regimes, whereas water productivities in water-saving treatments were as high as 1.9 kg grain m^{-3}. Water productivity was higher in the ASNS regime than in the CS regime for all three experiments and was statistically significant in Tuanlin in 2000 and at PhilRice. High water productivities at PhilRice were associated with high yield and low seepage and percolation rates (see also below).

Hydrology

Figure 1 gives the ponded water depths. At Tuanlin in the ASNS regime, plots were nonsubmerged for a total of 50 days in 1999 and 43 days in 2000. At PhilRice, plots with the ASNS regime were nonflooded for 56 days. At Tuanlin, the water depth below field level represents the perched water table. This level was never deeper than 22 cm below the soil surface. Figure 2 shows the shallow groundwater depth at PhilRice. Except for the last few days of the season, the groundwater was never deeper than 20 cm below the soil surface. Because of this shallow groundwater level, the soil water potential (at 10 cm) was never lower than –20 kPa until the final drainage before harvest (see Fig. 2). The final drainage occurred simultaneously in the surrounding fields, causing the groundwater level to drop from around –20 to around –90 cm within 10–15 days. At the same time, the soil moisture potential decreased from 0 to nearly –40 kPa.

Soil moisture status during midseason drainage was affected by rainfall, causing a peak in the soil moisture potential. Small cracks in the soil started to develop at soil water potentials of –1 to –2 kPa, but cracks never penetrated the hardpan.

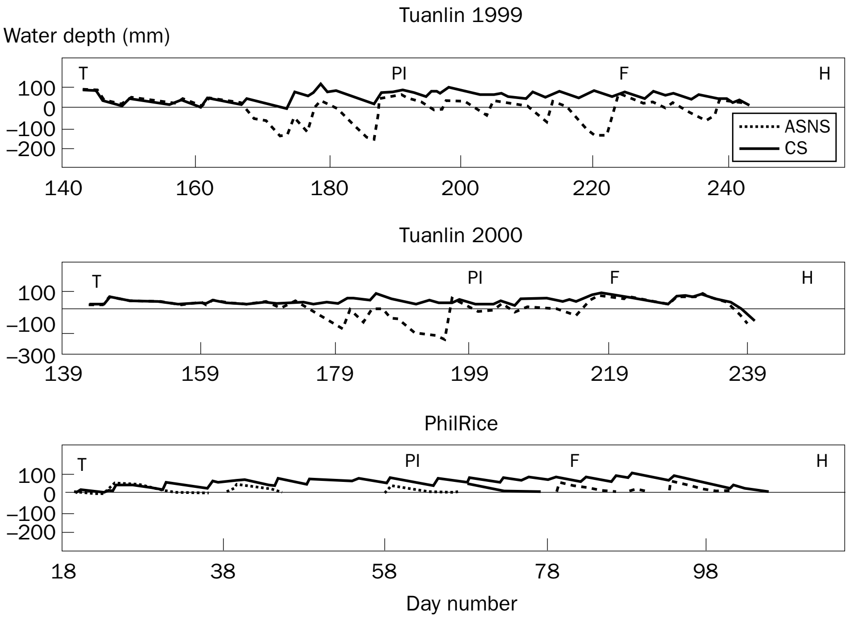

Fig. 1. Water depth of ASNS and CS regimes in Tuanlin in 1999, Tuanlin in 2000, and PhilRice in 2001, adapted from Cabangon et al (2001). Abbreviated crop stages are T = transplanting, PI = panicle initiation, F = flowering, and H = harvest.

Table 2 presents the seasonal seepage and percolation (SP) losses. Daily SP rates (mm d^{-1}) ranged from 3.9 mm d^{-1} in the CS regime in Tuanlin in 1999 to 0.9 mm d^{-1} in the ASNS regime at PhilRice. SP rates of 1–5 mm d^{-1} are typical for heavy clay soils (Bouman 2001). SP was lower in the ASNS regime than in the CS regime in all three experiments. This reduction was 87, 53, and 84 mm $season^{-1}$ for Tuanlin in 1999 and 2000 and PhilRice in 2001, respectively.

Direct measurement using the percolation ring showed percolation rates to be 0.8 and 1.1 mm d^{-1} at Tuanlin and PhilRice, respectively. In the 3-wk period after harvest, the percolation rate at PhilRice rose to 4.4 mm d^{-1}.

Discussion and conclusions

By keeping the rice field alternately flooded and drained, 13–16% irrigation water was saved without affecting grain yield significantly. This is in line with reports from Choudhury et al (1991) and De Dios et al (2000). The higher yield under the ASNS regime at PhilRice could be related to enhanced oxygen supply in this silty clay soil. Greenland (1981) stated that a minimum percolation rate of 10 mm d^{-1} is required for high yields. He argues that this percolation rate ensures the removal of toxic materials and an ample supply of oxygen. Ponnamperuma (1984) argues that a percolation rate of at least 1.5 mm d^{-1} is necessary to meet the oxygen demands of roots in flooded soil.

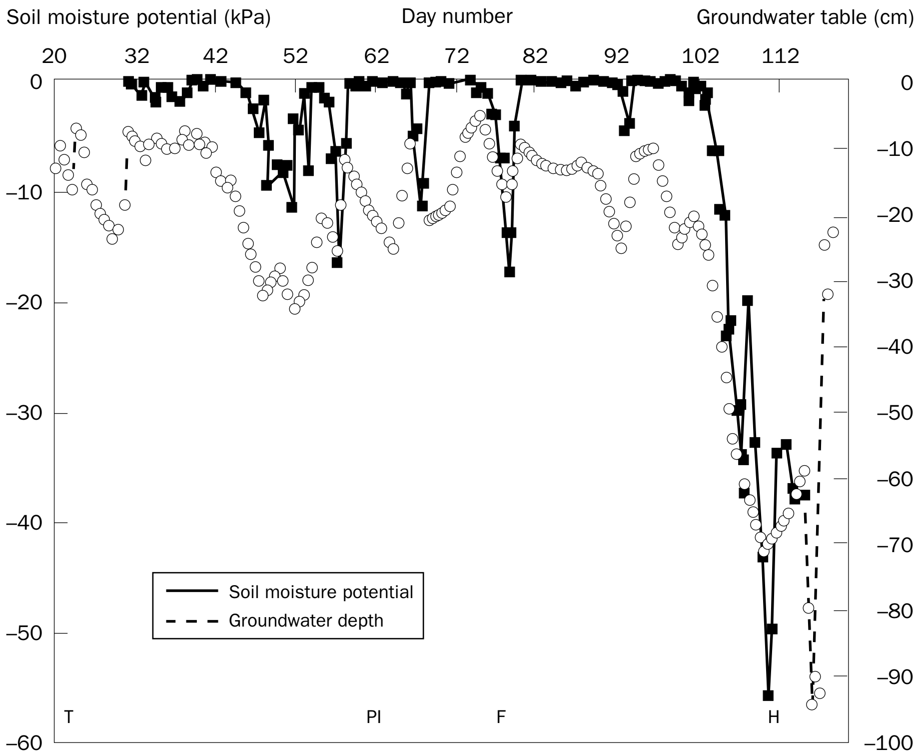

Fig. 2. Soil moisture potential and groundwater depth in the ASNS regime at PhilRice; abbreviated crop stages are T = transplanting, PI = panicle initiation, F = flowering, and H = harvest.

Water productivity was significantly higher in the ASNS regime than in the CS regime in two out of the three experiments, indicating higher resource-use efficiency of water. There might be an underestimation in the total water input in ASNS plots because the groundwater was not included in the inputs. This underestimation could have resulted in an overestimation of the water productivity. Therefore, we recommend testing ASNS regimes on a larger scale to see the effect of groundwater on the performance of the rice crop in this regime.

Wang et al (2001) reported that plant physiological processes such as photosynthesis and nutrient uptake remain unaffected when soil moisture potential is above –25 kPa. The soil moisture potential at PhilRice did not exceed this threshold until 2 days before harvest. The tensiometer readings may therefore confirm that the crop was not stressed during the cropping season. Lu et al (2000), however, already found a reduction in net assimilation rate in a japonica cultivar when the soil water potential reached –10 kPa in a light clay soil. They reported a significantly lower grain yield in the ASNS regime than in the CS regime.

This research was conducted in lowland areas with a moderate to heavy soil texture and a shallow groundwater table (less than 50 cm below field level). Although the percentage of days with nonsubmerged conditions was 38–59%, water availability for the rice plants below the soil surface was not (or hardly) affected by the aboveground water regime. It is uncertain what effects the ASNS regime will have on crop growth in areas with a significantly deeper groundwater table (deeper than 50 cm below field level). On lighter-textured soils, percolation rates increase and the groundwater table declines, which was also observed by Kampen (1970) and Wickham and Singh (1978). Seepage and percolation will become a more important water loss on lighter-textured soils. The estimated SP could have been influenced by surrounding fields with CS regimes because of differences in water head.

Lu et al (2000) reported that water consumption in ASNS was higher than in CS because, in their experiment, soil cracks developed and became the major route of water percolation. The groundwater table in their experiment was deeper than 1 m (Hirasawa, personal communication). Soil crack management and strict avoidance of hardpan cracks in the ASNS regime are therefore essential to save water rather than lose water on a field scale (Bouman and Tuong 2001).

We conclude that, in areas with a shallow groundwater table, small but significant irrigation water savings can be achieved in lowland rice areas by reirrigating the field after a period of soil drying without reducing grain yield. The duration of the nonsubmergence periods should be decided upon depending on groundwater table, soil texture, and the formation of deep cracks. Optimal water regimes for areas with a deeper groundwater table require further testing as surface water becomes more important for the water supply of the rice plant.

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Water management of rice in southern New South Wales, Australia

J.A. Thompson

The Australian rice crop is grown on the Riverine Plain with surface water supplied from the Murray and Murrumbidgee rivers and their associated creek systems. A few crops are irrigated with groundwater. The majority of the crop is grown in ponded water from sowing or the 3-leaf stage. Average growing-season evapotranspiration is 1,100–1,200 mm, with only 160 mm (range 30–350 mm) being contributed from rainfall. Daily evapotranspiration averages 9–10 mm d^{-1} from late tillering to flowering and can be as high as 15 mm d^{-1}. More than 50% of the water delivered to the irrigation areas is used for the rice crop; thus, the crop's water requirement is constantly under scrutiny. The industry has developed a policy that limits the area of rice that can be grown on an individual farm. Rice production is also restricted to soils considered suitable for rice, that is, those where drainage below the root zone is less than 200 mm ha^{-1}. Investigations into irrigation strategies to reduce the length of ponding have shown that there is some scope to reduce water use before panicle initiation, although weed control, particularly of barnyardgrass, is less effective. There is increasing pressure to provide more water for "environmental flows" in the river systems, thus reducing farmers' water entitlement. Mechanisms are in place to allow the transfer of water from farm to farm and to carry over unused water to the following season.

The Australian rice crop is grown on the Riverine Plain in New South Wales (33–36^{o}S) with surface water supplied from the Murray and Murrumbidgee rivers and their associated creek systems. The water is delivered to crops by a network of channels maintained by irrigation companies or it is pumped directly from the river or creek by the landholder. A few crops are irrigated entirely or partially with groundwater pumped from deep aquifers. More than 2,300 farms produce from 1.2 to 1.6 million t of paddy rice per year. The most recent harvest (2001) produced 1.7 million t from a harvested area of 184,000 ha, with an average yield of 9.47 t ha^{-1}. This was a record year for production, area, and yield (Anonymous 2001). Eighty percent of the rice produced in Australia is from semidwarf medium-grain japonica varieties. Australia exports around 85% of its annual production as value-added packaged and branded product. Compared with other crops, rice consumes large amounts of water, the cost of which accounts for 25–30% of the variable costs of rice production. More than 50% of the water delivered to irrigation areas is used for rice production; thus, the crop's water requirement is constantly under scrutiny. This paper describes the water management of rice and discusses the scope for increasing its water-use efficiency in southern New South Wales.

Water use and land suitability

Rice seeds are either aerially seeded into flooded bays (fields) or sown directly into dry soil and then watered. The majority of the crop is grown in ponded water from sowing or the 3-leaf stage. The average evapotranspiration during the whole growing season is 11–12 ML ha^{-1} (1,100–1,200 mm), with only 1.6 ML ha^{-1} (160 mm; range 30–350 mm) being contributed from rainfall (Humphreys et al 1994). Daily potential evapotranspiration averages 9–10 mm d^{-1} from late tillering to flowering and can be as high as 15 mm d^{-1}. In the past, irrigation water has been readily available, but increasing demand and competing water uses throughout regional communities have put pressure on the availability and cost of water for irrigation. State and federal governments have policies to control the distribution of the available water to all water users and also to satisfy environmental requirements (Beecher et al 2000). Beecher et al (2000) stated that, "Rice water use, when measured precisely and safeguarded from interference, is the ultimate test for rice land suitability but measurement is difficult and expensive to undertake on a large scale. Consequently, measured rice water use is most effectively used to identify 'leaky' fields that should be assessed in more detail by techniques such as EM 31 survey." The supply of water to a field for growing rice has been measured for many years and used as a broad indication of soil suitability. Since 1986, the measurements have been actively compared with target limits as an indicator of potentially unsuitable land for rice growing where groundwater accessions could exceed acceptable limits.

The suitability of the land used for rice growing is primarily determined by the ability of the soil to pond water without allowing excessive accessions to the water table or environmental harm to other land. The characteristics of the soil must be such that the water resource is used efficiently and the flow of water away from the root zone of rice is minimal. The identification of potentially suitable soil, supported by acceptable water use of rice, determines the rice-approved area of a farm. At present, accessions below the root zone are limited to less than 2 ML ha^{-1} (200 mm). The entire rice-approved area of a farm cannot be planted to rice in one season. Limits are imposed on the rice area to reduce the amount of water applied to the landscape. In turn, these limits serve to minimize groundwater recharge and the effect of rice growing on the surrounding environment. Guidelines are based on the concepts of hydraulic loading, irrigation intensity, or a defined maximum area per license, depending on the policy of the local irrigation authority (Beecher et al 2000).

Increasing water-use efficiency

Intermittent flooding (alternate wetting and drying)

An experiment at Yanco in the Murrumbidgee Valley in 1981-82 examined the performance of the medium-grain variety Calrose under different irrigation strategies (Heenan and Thompson 1984a). The research indicated that applying a flood irrigation (irrigation water was ponded for 2–3 hours—sufficient time to saturate the root zone) at 7-day intervals throughout the season produced low yields and rice of unacceptable quality. However, when permanent water was applied from panicle initiation onward, both yield and quality compared favorably with a conventionally managed crop that had permanent flood applied from the 3-leaf stage onward. This technique of "delayed flooding" reduced total water use by 23%. Further work in 1982-83 and 1983-84 confirmed that water savings of 22–26% can be obtained by using intermittent flooding during the vegetative phase followed by permanent water from panicle initiation onward (Heenan and Thompson 1984b). Intermittent flooding is currently being reevaluated using modern semidwarf varieties. The timing of the irrigations is being scheduled using cumulative evapotranspiration in lieu of the fixed 7-day interval used in the earlier studies. The effect of midseason drainage on rice yield and water use is also being examined. Finally, intermittent flooding will present challenges for weed control and fertilizer management.

Saturated soil culture (raised beds)

In the raised-bed layout, irrigation water is maintained in the furrows between the beds rather than ponded over the entire soil surface. Research in the Burdekin River Irrigation Area in Queensland (20°S) indicated that the water use of rice grown on raised beds was 32% less than when grown under conventional permanent flooding (Borrell et al 1997). At this site, drainage below the root zone was greater than the potential evapotranspiration of the rice crop. While recognizing that there are likely to be agronomic constraints to rice production on raised beds in southern Australia, especially with weed control and cold-temperature effects on sterility, investigations of potential water savings have continued. These investigations, conducted over four growing seasons, recorded a potential water savings of only 10%. A similar reduction in grain yield (11.6 t ha^{-1} for the ponded treatment, 10.2 t ha^{-1} where water was maintained in the furrows) results in no improvement in water-use efficiency. In two of the four seasons, the crop grown on the raised beds recorded a lower harvest index.

Sowing method

Several experiments have compared the water use from a combine-sown crop (dry-seeded) with an aerial-sown crop (wet-seeded). Water use and grain yields were similar (unpublished data, Liz Humphreys, CSIRO Land and Water, Griffith; own unpublished data). Any potential water savings from not ponding until the 3-leaf stage are likely to be negated by the slightly longer growing period of the dry-seeded crop.

Drainage recycling
Rice growers are implementing drainage recycling systems. They are an important feature of on-farm irrigation layouts because of the need to maximize the use of irrigation water and minimize off-farm effects of agriculture. Recycling systems enable the retention, on-farm, of excess water that flows from irrigated fields and water that has been treated with pesticides or that contains nutrients from fertilizer applications. Withholding periods for treated drainage water are specified for all irrigation areas.

Water costs and water trading

The cost of irrigation water supplied by irrigation companies to growers is about US$10 per ML. This cost is continually increasing as the irrigation companies need to be economically viable. The supply of "bulk" water from the state authority to the irrigation companies is reviewed annually and continues to increase. Where the water is pumped from the river or creek, the cost to growers is about $5. The cost to growers of groundwater supplied to the crop is approximately $12 (a charge for the water and fuel costs for pumping).

Mechanisms are in place that allow the transfer of water from farm to farm within an irrigation area. For example, Murray Irrigation Limited conducts a water exchange for its 1,800 clients. Since 1997-98, there have been on average 1,200 "sales" per season, with the price paid ranging from $5 to $40 per ML. This season (2001-02), the price paid has ranged from $12 to $35. The cost per ML is not controlled and depends on the buyer's assessment of water availability and the seller's assessment of the current value of the asset. Most of the water currently traded is purchased by rice growers because, as for most of them, despite high water use per hectare, rice production is their most profitable and convenient enterprise. Farmers can also carry over any unused entitlement to the following season. This ensures at least some water if below-average rainfall during winter months results in a low irrigation water allocation for the growing season. Up to 40% of the irrigation water allocation can now be carried over from one season to the next.

Conclusions

The high daily rates of evapotranspiration experienced during the reproductive period of the Australian rice crop reduce the scope for employing water-saving strategies without the risk of a substantial yield penalty. From panicle initiation to flowering, crop growth rates are as high as 250–300 kg ha^{-1} d^{-1}, thus requiring a nonlimiting supply of water to the root zone of the crop. The growing of rice is restricted to soils that exhibit an acceptably low level of deep percolation and where the relatively flat topography precludes seepage from being a problem in the measurement of water use for rice.

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System of Rice Intensification

Reducing water use in irrigated rice production with the Madagascar System of Rice Intensification (SRI)

N. Uphoff and R. Randriamiharisoa

The System of Rice Intensification (SRI) developed in Madagascar increases yields substantially, 50% to 100% or more, while requiring only about half as much water as conventional rice. There is no need for different varieties or to purchase external inputs. Most water-saving methods to date show little decline in yield or, at most, small gains in output. The large increase in the productivity of irrigation water use with SRI could make water savings more attractive, compensating farmers well for the extra labor or expenditure involved. The returns to land, labor, capital, and water are all increased by the use of SRI practices.

This paper discusses the SRI and its increasing acceptance outside of Madagascar. It reviews the common thinking that rice is an aquatic or at least hydrophilic plant, which is contradicted by SRI experience. Continuously flooded soils constrain root growth and contribute to root degeneration. They also limit soil microbial life to anaerobic populations. This excludes contributions to plant performance from mycorrhizal fungal associations that are of benefit to most plant species. Keeping paddy fields flooded also restricts biological nitrogen fixation to anaerobic processes, forgoing possibilities for aerobic contributions. Evidence is presented that the SRI produces different phenotypic expressions of existing genetic materials. SRI methods have been able to raise yields of any rice variety, but the highest yields have come from improved high-yielding varieties. Factorial trials in Madagascar explain synergistic dynamics among the SRI practices that account for 100–200% increases in yield. The main constraints to SRI use (requirements for more labor, skill, and water control) can be reduced with more experience or investment.

This paper discusses the System of Rice Intensification (SRI) developed in Madagascar in the 1980s and considers how it could create incentives for reducing the use of water in irrigated rice production without loss of output. SRI methods have been seen to increase yields substantially, often by 100% or more. So, since SRI requires only about half as much water to grow a crop of rice as with conventional methods, it can raise the productivity of irrigation water in rice cultivation by as much as four times, or even more (Uphoff 1999, Stoop et al 2002).

Several previous evaluations have found that the present levels of rice yield can be achieved with less application of irrigation water (e.g., Guerra et al 1998). When standard agronomic practices are used, however, there are small gains, if any, in output—either yield does not decline with less application of water or the gains are in the range of 10% to 25% (e.g., Ramasamy et al 1997).

Certainly, even small increases are desirable if they are accompanied by water savings. But such increases may not be sufficient to encourage farmers to reduce water use if this requires more time and labor. Sufficient increases in output will be necessary to compensate farmers for the extra expenditures involved when using less water.

The challenge of getting farmers to adopt water-saving methods is complicated by the fact that most of the benefits from water savings accrue to persons other than those who invested in the effort to make the savings, that is, to downstream farmers or to other water users for domestic or industrial purposes. Farmers' incentives to use less water will be limited if there is simply no loss or little gain from these measures. Alternative cultivation practices that provide definite net gains to farmers—through increased income, reduced expenses, or both—are important for the adoption of water-saving practices. The SRI is such a practice, offering rice-growing farmers yield increases and other benefits when they apply less water, provided this is done in conjunction with other changes in how they manage plants, soil, and nutrients.

The value of SRI practices is now being seen in other countries beyond the country where the methodology was developed (de Laulanié 1993). The first trials outside Madagascar were done by two of our Wageningen consortium partners, Nanjing Agricultural University (NAU) in China and the Agency for Agricultural Research and Development (AARD) in Indonesia. These trials satisfied researchers at these institutions that the combination of agronomic practices called SRI, including reduced application of irrigation water, is worth further evaluation.

- The initial SRI yields at NAU in 1999 were 9.2–10.5 t ha^{-1}. While it is possible to obtain such yields with certain existing technologies and hybrid rice varieties in China, this output was attained using only half as much water as usual and with fewer expensive inputs.
- At the AARD station at Sukamandi, SRI trials in 1999-2000 from the first (dry) season produced 6.2 t ha^{-1}, about a 40% improvement over usual yields, and then 9.5 t ha^{-1} in the following (wet) season. These gains were evaluated as cost-effective and, after further evaluation in 2000 and 2001, components of the SRI methods are being incorporated into AARD's new integrated crop

and resource management (ICM) strategy for the whole country, making adjustments for local conditions as appropriate (Gani et al 2002).

Since then, positive results from SRI methods have been reported from the Philippines, Cambodia, Myanmar, Lao PDR, Sri Lanka, Bangladesh, Gambia, Sierra Leone, and Cuba. Yield increases of 50% to 100% are common, with sometimes even a tripling of yield (Kabir 2002, Yamah 2002, Ceesay 2002).

Yield statistics are the simplest and most dramatic measure of performance, but more important is *factor productivity*, since this contributes the most to development and to improvements in farmers' welfare. The SRI is particularly interesting because it can raise the productivity of land, labor, and capital as well as of water all at the same time. These gains in productivity are achieved by changing plant, soil, water, and nutrient management practices that have been used for centuries, even millennia, thereby achieving different phenotypical expression of rice genetic potential (Uphoff 2001). These practices capitalize on the availability of abundant (free) oxygen and nitrogen in the atmosphere either directly through soil aeration or indirectly by fostering larger and more diverse microbiological communities. These contribute to biological nitrogen fixation (BNF) and solubilization of P and other nutrients, and different soil conditions permit the growth and benefits of mycorrhizal fungal associations and endophytic rhizobia, two examples of soil microbiological effects becoming better known in recent years.

An additional benefit from cultivating rice in unflooded paddies, as done with the SRI during most of the growing season, would be some reduction in greenhouse gas emissions (Roger and Ladha 1992). Flooded paddies contribute as much as 25% of the total annual emissions of methane (Liesack et al 2002).

Rethinking conventional wisdom

The SRI calls into question the common belief that rice is an aquatic or at least hydrophilic plant. There are several reasons, with support in the literature, for questioning this prevalent thinking. Just because rice can survive in soil that is inundated (hypoxic) does not mean that it will thrive under such conditions. Rice has been grown under flooded conditions mostly because these make weed control easier or even unnecessary, thereby saving labor.

Without scientific confirmation, the observation that rice is able to grow in flooded paddies has been extrapolated into an idealization that rice performs better and even requires standing water to be most productive (De Datta 1981). It is true that rice grows more abundantly in standing water than it does under upland (unirrigated) conditions. But this does not make continuous flooding the best practice. Little attention has been paid until recently to an optimizing middle range of water management in which soil is kept moist but mostly aerobic through controlled water application or alternate wetting and drying of paddies. And until the SRI was introduced, little work was done on how changes in other cultivation practices could make reduced-water rice production more profitable than with regular irrigation.

Several observable physiological features of rice grown under continuously flooded conditions suggest that these are not ideal circumstances for the best rice plant performance:

- A month after transplanting, about 75% of the rice roots growing in saturated soil are concentrated in the upper 6 cm of soil as they remain near the surface to obtain whatever dissolved O_2 they can get from irrigation water (Kirk and Solivas 1997). Such truncated root systems can access nutrients from only a limited volume of soil, having to rely mostly on nutrients provided through fertilizers. Conversely, when rice is grown with intermittent flooding and with other SRI methods, roots extend downward 30 to 50 cm (Barison 2002, Tao et al 2002).
- When rice plants are grown under continuously flooded conditions, much of the root cortex disintegrates to form aerenchyma (air pockets) (Kirk and Bouldin 1991). This process occurs both in varieties bred for irrigated cultivation and in so-called "upland" varieties. However, neither irrigated nor upland varieties form aerenchyma when they are grown in well-drained soil (Puard et al 1989). The difference between these two categories of rice is that the former are able to create larger and more regular aerenchyma that enable roots to continue functioning and to survive longer in flooded soil. Formation of aerenchyma appears to be a suboptimizing rather than an ideal adaptation to hypoxic conditions.
- By the time of flowering when grain production begins, about 75% of the roots of rice plants that are growing in continuously saturated soil are degenerated, whereas there is little or no degeneration of roots growing in soil that is well drained (Kar et al 1974).

These changes in rice plants' root systems and in their capacity to take up nutrients during their growth cycle, and particularly during the reproductive phase after panicle initiation, are acknowledged in the literature. Because these changes are regarded as "senescence," something natural rather than induced by alterable growing conditions, they have not been regarded as constraints to production. Rice plants have been assumed to be well adapted for growth in flooded fields (Kirk and Bouldin 1991, De Datta 1981).

The results with SRI methods indicate that reducing the use of irrigation water in rice production is desirable not just for the benefits that can be gained from water savings; this can also contribute to more efficient use of the land, labor, and capital involved in rice production. Part of this gain can be attributed to the SRI plants' more efficient uptake of nutrients owing to their better developed root systems when not inhibited by cultural practices.

Soil chemistry and biology in flooded vs unflooded soils

One important consequence of growing rice in continuously flooded paddies is that aerobic microbes, including particularly fungi, cannot grow in inundated soil. For one thing, rice plants cannot benefit from the services of mycorrhizal associations, which are increasingly recognized as important intermediaries in the nutrition of most terrestrial plants (Habte and Osario 2001). Mycorrhizal fungi that "infect" roots help maintain a balance in the supply of nutrients to the plant as well as provide valuable protective services. They can increase the soil volume accessed by as much as 100 times compared with the unaided (uninfected) root. Plants with mycorrhizal fungi can grow well with just a fraction of the P required for unassisted plants, for example (Habte and Osario 2001). However, since fungi cannot survive under hypoxic conditions, continuously irrigated rice has forgone the benefits of their associations for centuries, even millennia.

The beneficial effects of aerobic soil bacteria known as rhizobia have long been known for their intimate association with the roots of leguminous plants, living in root nodules and fixing nitrogen biologically. Recent research is showing that rhizobia, which can grow as endophytes in and on roots (without nodulation), contribute to increased rice production even though this plant is not a legume (Yanni et al 2001). The increase in both vegetative and reproductive biomass is apparently attributable to more efficient acquisition of soil nutrients (N, P, K, Mg, Ca, Zn, Na, and Mo) rather than to BNF. Determining the effects of soil microbes on plant performance is a complicated and difficult process, and research on plant growth promotion through these processes is still in its early stages.

Beneficial soil chemistry effects from growing rice in flooded soils are well known, having been documented by Ponnamperuma (1972), Sanchez (1972), and others. These effects are surely important, but there has not been equivalent research on the beneficial effects of aerobic soil management with rice or, more relevant for SRI, of alternating aerobic and anaerobic soil conditions. What is important is to know the net effects of different management practices and of possible synergy between them. The empirical results achieved with SRI methods suggest that the greatest net benefit is from a mix of aerobic and anaerobic conditions.

With flooded conditions, one forgoes biological nitrogen fixation from aerobic microorganisms (Döbereiner 1987, Boddy et al 1995), even though about 80% of the bacteria in the rice plants' rhizospheres have the potential for BNF (Watanabe et al 1981). Magdoff and Bouldin (1970) documented substantial increases in BNF when aerobic and anaerobic soil horizons are mixed together continuously. How significant BNF can be for paddy-grown rice when the soil is better aerated than with continuous flooding is not known because it has scarcely been investigated. It is known that, when soils are alternately wetted and dried, as is done with SRI water management, very large increases in soluble P from organic sources can occur (Turner and Haygarth 2001).

The SRI that includes nonflooding management practices gave some remarkable yields from soils that were assessed to be, in standard chemical analysis terms, some of the poorest in the world (Johnson 1994). Given present understanding of soil-plant-nutrient relationships, it is hard to explain how farmers around Ranomafana National Park in Madagascar could average 8 t ha^{-1} without fertilizer applications after getting 2 t ha^{-1} before, with some even reaching 16 t ha^{-1} (Uphoff 1999). This was done on soils that are low to very low in cation-exchange capacity in all horizons, with only 3–4 ppm of available phosphorus (Johnson 1994). With current soil chemistry theories, it is hard to account for a quadrupling of yield on such soils. The SRI therefore opens some interesting avenues for research that assesses soil biologically, especially its microbiological dynamics. It should be useful to investigate in more detail the balance of positive and negative soil chemistry effects from flooding vs nonflooding.

Assessing the effects of changes in soil and water management practices

Factorial trials have shown that the increases with the SRI are attributable only partly to the different plant management practices. A good share of the increase appears to derive from different soil and water management, particularly from keeping the soil unsaturated, periodically if not continuously, so that rice plant roots do not need to form aerenchyma and do not degenerate.

Barison (2002) compared rice plants grown with SRI practices (on mostly aerated soil) and conventional practices (saturated soil) for 108 farmers in four different areas in Madagascar who were using both methods on their farms. This design controlled for differences among farms and farmers. He found that plants of the same variety took up 90% more N and K, and 60% more P, under SRI management compared with those conventionally grown, with no change in harvest index. SRI water management practices along with plant, soil, and nutrient practices contributed to this result, which was accompanied by a doubling of yield (see McHugh et al, this volume).

As presented in the next section, one of the main SRI practices is keeping the soil moist but well drained, that is, never saturated with continuously standing water, thereby avoiding root hypoxia during the vegetative growth phase. After panicle initiation and until ripening, a thin layer (1–2 cm) of water is maintained on fields. Before that, during the vegetative growth phase, the soil is actively aerated by two to four weedings with a simple mechanical rotating hoe.

There are not yet any fixed recommendations for water management, only a principle to be followed of keeping soil well aerated during the vegetative growth phase. What will be the best water management practices for SRI in terms of amount and timing of water application will depend on soil characteristics as well as on varietal and other differences. Not enough research has been done evaluating the implications of soil, varietal, and other differences to know how little water can be applied, and at what intervals, when plants, soil, and nutrients are being managed according to SRI principles. Conclusions drawn about the best water applications based on conventional agronomic practices may not be relevant for SRI-grown plants because of interactive effects with other factors such as seedling age and planting density.

A review of SRI practices

The practices brought together under the SRI rubric have been referred to already, but they are stated here in a systematic way. The SRI involves several practices that are presented to farmers as starting points rather than as strict instructions (Rabenandrasana 1999):

- Transplant young seedlings, usually from 8 to 12 days old, and certainly less than 15 d old. The exact limit depends on biological processes, measured in terms of phyllochrons (Katayama 1951, Nemoto et al 1995), rather than being determined by calendar time. Farmers should transplant seedlings with only two small leaves when the seed sac is still attached to the root. Early transplanting preserves potential for tillering and root growth that will be lost if transplanting is done after the start of the fourth phyllochron (de Laulanié 1993).
- Plant single seedlings rather than several seedlings together in a hill. Sometimes 2 seedlings per hill may be optimal for certain soil conditions, which can be determined through simple experimentation. The purpose of this recommendation is to avoid root competition that inhibits vigorous root growth.
- Plant seedlings in a square pattern with wide spacing. Starting with spacing of 25 × 25 cm is recommended, but, with soil that is rich in biological terms, wider spacing (30 × 30 cm or 40 × 40 cm, up to 50 × 50 cm) with fewer plants per m^2 gives higher yield.
- Plant quickly and carefully to avoid trauma to seedling roots. Seedlings are planted fairly shallow (1–2 cm deep) and care is taken so that the root tip is not inverted upward by thrusting the plant straight downward into the soil. An inverted tip delays resumption of plant growth until the plant is once again oriented downward.

  Then, after careful plant establishment, which is feasible because many fewer plants are being set out,
- Maintain moist but aerated soil during the vegetative growth phase, either (1) by regular applications of small amounts of water daily that keep the field moist but never saturated, with some periods of 2–6 days in which the field is not irrigated and allowed to dry out to the point of surface cracking, or (2) by alternate wetting and drying (AWD) of the field for periods of 4–5 days each during the growth period. McHugh (2002) and Barison (2002) found in their recent research in Madagascar that many farmers using SRI methods prefer AWD because it requires less labor. As noted above, after panicle initiation, a thin layer of water (1–2 cm) is maintained.
- Weed early and often with the rotating hoe promoted by IRRI in the 1960s, weeding at least twice, starting 10–12 DAT and repeated at 10–12-d intervals. Three or four weedings are recommended to enhance soil aeration. Preliminary data show yield increases of 0.5 to 2.0 t ha^{-1} with each additional weeding beyond two (Uphoff 1999, Randriamiharisoa 2002). This

needs to be evaluated more extensively to predict what the returns from weeding can be.

- Apply compost preferably on the crop preceding the rice crop to give it more time for decomposition and buildup of diverse microbiological communities in the soil. Fertilizer can be used productively with the SRI; indeed, the SRI was developed in the 1980s with the use of fertilizer. The switch to recommending compost with other SRI practices came after a termination of government subsidies in Madagascar made fertilizer too expensive for small farmers to afford. Experience showed that compost gave better results, particularly over time. Farmers have often been reluctant to apply compost on staple grain crops because of the amount of labor required. But if SRI practices double or triple yield, this can provide incentive for farmers to make and use compost, possibly growing leguminous plants such as tephrosia and crotalaria on otherwise wasteland to have more available biomass.

Direct evidence that SRI practices affect rice plant growth

Three phenotypic changes can be seen and measured in rice grown with SRI practices:

1. *Increased tillering*: Averages of 20–30 tillers per plant are fairly easy to obtain, and in some well-managed fields these reach 50, even 70, tillers per plant. This difference is easy to see in SRI fields. Also, there is less senescence of leaves during the grain-filling period, with the flag leaf remaining dark green until grain maturation occurs, probably reflecting the continuing functioning of plant roots.
2. *Greater root growth*: This is the key to SRI performance though it is unseen. Root pulling resistance with SRI plants, using the measurement test developed at IRRI (O'Toole and Soemartono 1981, Ekanayake et al 1986), is about 5 times greater per plant than for rice plants grown under conventional conditions (Joelibarison 1998).
3. *More grain filling*: With SRI practices, a positive correlation is found between the number of tillers per plant and the number of grains per panicle (Uphoff 1999). This contradicts the view of rice in the literature, which maintains that this correlation is naturally negative (Ying et al 1998). The inverse relationship that has been observed between tillering and grain filling occurs in conventionally grown rice plants because they have become practically closed systems because of their root degeneration and this causes diminishing returns to tillering. The belief that there is a negative correlation between tillering and grain filling, and thus a yield ceiling within rice plants' genomes as presently constituted, has led to efforts to redesign the rice plant to create a new plant type, a so-called "super-rice," by plant breeding methods (Khush and Peng 1996).

With SRI practices, keeping rice plant roots intact through different water management methods and less total application of water, we have found no evidence of a yield ceiling. With these methods, farmers can produce panicles with 200–300 grains, and some with as many as 400 or 500, even 600, grains. The SRI's combination of management practices gives expression to impressive genetic potential already existing within the rice plant.

Varietal improvement

We have seen these effects with all varieties that have been used so far. However, some varieties respond more vigorously and beneficially to these management methods than do others. There is good news for plant breeders from our experience thus far in that the highest yields with SRI methods in Madagascar and Sri Lanka have come from improved, that is, high-yielding varieties, descendants of IR15 (12 t ha^{-1}), IR46 (16.5 t ha^{-1}), BG-358 (17 t ha^{-1}), and Taichung-16 (21 t ha^{-1}) (Tang-Po 1996, Uphoff 1999). In China, SRI methods are being used to top up the yields of super high-yielding hybrid varieties, with yields as high as 16.5 t ha^{-1} (Yuan 2002).

There should be no contradiction or conflict between the SRI and genetic improvement efforts. What is important is more open acknowledgment and exploration of the contributions of agronomic practices and the essential role of the environment in $G \times E$ interactions (Lewontin 2000).

Statistical evidence of synergy among SRI practices

To have a positive correlation between tillering and grain filling, there needs to be reinforcement between tillering and root growth, with each process supporting the other: root growth supports tillering and vice versa. The emergence of tillers and roots is biologically linked in all grass species such as rice, with both being components of the basic unit of plant growth in grasses, the phytomer, that emerges from meristematic tissue (Nemoto et al 1995).

Two sets of multifactorial trials have been carried out by the Faculty of Agriculture at the University of Antananarivo in Madagascar. These studies have shown the synergistic effects of combining SRI practices in comparison to what results from standard practices. The trials (N = 288 and N = 240, respectively) were designed to test whether or to what extent the hypothesis of synergy that underlies SRI can be observable empirically.

- Rajaonarison (2000) conducted research on the SRI at the Centre de Baobab on the west coast of Madagascar near Morondava in the minor season of 2000. This location and season were chosen because many farmers around the Centre have adopted the SRI so they could help to establish and manage the plots. Also, although this location has poor soils and yields are not very high in the minor season, there are fewer pest and disease problems whose effects could obscure agronomic effects.
- The second set of trials was carried out by Andriankaja (2001) in the village of Anjomakely, 18 km south of the capital Antananarivo on the high plateau. This presents a very different environment, about 1,200 m elevation com-

pared with 100 m, and with better soils overall and more contrasting day-night temperatures.

In both sets of trials, six factors were evaluated: either rice variety or soil quality, along with water management, seedling age, plants per hill, fertilization, and spacing. Weeding practices were not evaluated in these trials and were the same for all plots. Adding this factor would have doubled the total number of plots to be established and managed, to 576 and 480, respectively. With six factors, there were 96 combinations ($2 \times 2 \times 2 \times 2 \times 3 \times 2$) to be evaluated. The 2.5×2.5-m plots were laid out according to a randomized modified Fisher block design with three replications. Because of the impossibility of completely controlling subsurface water movement, the water management variations were all done within subblocks, and, for the same reason, the fertilization variations were done in sub-subblocks. The other four factors were then combined randomly in the 288 or 240 plots.

The spacing factor was evaluated with distances of 25×25 and 30×30 cm, both within the SRI range. There was no difference in the spacing trials at Morondava (identical means of 5.28 t ha^{-1} for both sets of trials, each N = 144) and no significant difference (only 0.08 t ha^{-1}) at Anjomakely (each set of trials, N = 120). So, the evaluation of results was really for five factors, not differentiating spacing. All of the averages being reported and evaluated are thus from six replications rather than three.

- In the first set of trials, variety effects were evaluated, comparing yields with SRI vs conventional practices, using an improved variety (2798) in half the trials and a traditional variety (*riz rouge*) in the other half, with soil being as similar as possible for all trials.
- In the second set of trials, soil-quality effects were measured, comparing better soil (clay) with poorer soil (loamy) in two subsets of trials, all planted with the same variety (*riz rouge*). On the poorer soil at Anjomakely, no control plots were established for the fertilization trials (adding either NPK or compost), so the total number of trials there was 240 instead of 288.

Table 1 shows the values of the other factors evaluated in the trials.

Table 1. Values of other factors evaluated in trials.

Factor	SRI practice	Conventional practice
Water management	Aerated soil	Saturated soil
Seedling age	8 d	16 d (Morandava) or 20 d (Anjomakely)[a]
Number of seedlings	1 per hill	3 per hill
Fertilization	Compost	NPK fertilizer

[a]These ages are equivalent in terms of phyllochrons given differences in temperature at the two locations.

Results

The yields at Morondava with standard practices were 2.11 and 2.84 t ha^{-1} with the traditional or high-yielding variety and 5.96 and 6.83 t ha^{-1} with SRI practices, an average increase of 160%. At Anjomakely, with *riz rouge*, standard practices yielded 2.04 and 3.00 t ha^{-1}, respectively, on poor and good soil, and 6.39 and 10.35 t ha^{-1} with SRI practices on these soils, an average increase of 238% (Table 2). One can see how each of the component practices contributes to the increase, with the largest increases across all trials coming when all of the SRI practices are used together.

These parallel results show how the addition of any one, two, or three SRI practices from among the four practices evaluated—aerated soil, 8-d-old seedlings, 1 plant per hill, and compost—all increase yield compared with the standard practice. However, the biggest average increase across all four comparisons came from using all SRI practices, which added almost 2 t ha^{-1} to yield beyond what could be produced by using any three of the four practices.

Our interest here is in differences in water management and in the possibilities for water savings with increases in yield. In Tables 3 and 4, the data from Table 2 are presented in terms of the effect on yield of maintaining aerated soil (AS) compared to having saturated soil (SS) throughout the growth period. For all combinations of practices, aerated soil gives a higher yield than does saturated soil. This finding is in line with Sayre and Moreño Ramos (1997), showing benefits of soil aeration as well as wide spacing with wheat.

It is interesting to compare the differences (gains) in yield for all of these combinations, as shown in Table 4, considering the different responses that are associated with using NPK or compost with either modern or traditional varieties, on poor soil, or on either better or poorer soil, with a traditional variety. The high-yielding variety responded consistently better to soil aeration with either NPK or compost than the traditional variety. There was likewise a higher response to soil aeration on better soil than on poorer soil. Such results invite further investigation, probably examining the effects of differences in soil microbiology (Randriamiharisoa 2002).

The absolute yield levels resulting from these different combinations of practices will vary when other varieties are used and on other soils and under other growing conditions. The consistency of yield patterns between the two sets of factorial trials suggests, however, that these relationships are likely to hold up. This conclusion is supported by the results seen with SRI practices over several years in Madagascar and now in a growing number of countries.

Table 2. Analysis of factorial trial results at Morondava, 2000, and Anjomakely, 2001, comparing effects of varietal and soil-quality differences with SRI vs non-SRI practices. Average yields in t ha^{-1}; SRI practices in *boldface italics.* Key: SS = saturated soil, *AS* = aerated soil, 16 = 16-d-old seedlings, *8* = 8-d-old seedlings, 3 = 3 plants hill^{-1}, *1* = 1 plant hill^{-1}, NPK = chemical fertilizer, *C* = compost.

Treatment	Variety			Soil quality		
	HYV[a] (N)	Traditional (N)	Av (N)	Better (N)	Poorer (N)	Av (N)
Standardized practices						
SS/16-20/3/NPK	2.84 (6)	2.11 (6)	2.48 (12)	3.00 (6)	2.04 (6)	2.52 (12)
+ 1 SRI practice						
S/16-20/3/***C***	2.69 (6)	2.67 (6)		3.71 (6)	2.03 (6)	
SS/16-20/***1***/NPK	2.74 (6)	2.28 (6)		5.04 (6)	2.78 (6)	
SS/***8***/3/NPK	4.08 (6)	3.09 (6)		7.16 (6)	3.89 (6)	
AS/16-20/3/NPK	4.04 (6)	2.64 (6)		5.08 (6)	2.60 (6)	
	3.39 (24)	2.67 (24)	3.03 (48)	5.25 (24)	2.83 (24)	4.04 (48)
1 SRI > standard practice	+0.55 t *P* = 0.021	+0.56 t *P* = 0.007	+ 0.55 t	+2.25 t	+0.79 t	+1.52 t
+ 2 SRI practices						
SS/16-20/***1***/***C***	2.73 (6)	2.47 (6)		4.50 (6)	2.44 (6)	
SS/***8***/3/***C***	3.35 (6)	4.33 (6)		6.86 (6)	3.61 (6)	
AS/16-20/***1***/NPK	4.10 (6)	2.89 (6)		6.07 (6)	3.15 (6)	
AS/16-20/3/***C***	4.18 (6)	3.10 (6)		6.72 (6)	3.41 (6)	
SS/***8***/***1***/NPK	5.00 (6)	3.65 (6)		8.13 (6)	4.36 (6)	
AS/***8***/3/NPK	5.75 (6)	3.34 (6)		8.15 (6)	4.44 (6)	
	4.19 (36)	3.30 (36)	3.75 (72)	6.74 (36)	3.57 (36)	5.15 (72)
2 > 1 SRI practice	+0.80 t *P* = 0.000	+0.63 t *P* = 0.000	+0.72 t	+1.49 t	+0.74 t	+1.11 t
+ 3 SRI practices						
SS/***8***/***1***/***C***	3.85 (6)	5.18 (6)		7.70 (6)	4.07 (6)	
AS/16-20/***1***/***C***	3.82 (6)	2.87 (6)		7.45 (6)	4.10 (6)	
AS/***8***/3/***C***	4.49 (6)	4.78 (6)		9.32 (6)	5.17 (6)	
AS/***8***/***1***/NPK	6.62 (6)	4.29 (6)		8.77 (6)	5.00 (6)	
	4.70 (24)	4.28 (24)	4.49 (48)	8.31 (24)	4.59 (24)	6.45 (48)
3 > 2 SRI practices	+0.51 t *P* = 0.000	+ 0.98 t *P* = 0.000	+0.74 t	+1.57 t	+1.02 t	+1.30 t
All SRI practices						
AS/***8***/***1***/***C***	6.83 (6)	5.96 (6)	6.40 (12)	10.35 (6)	6.39 (6)	8.37 (12)
All > 3 SRI practices	+2.13 t *P* = 0.000	+1.68 t *P* = 0.000	+1.91 t	+2.04 t	+1.80 t	+1.92 t

[a]HYV = high-yielding variety.

Table 3. Comparison of yield (t ha^{-1}) with different combinations of practices, comparing the effects of aerated soil (AS) vs saturated soil (SS). N = 6 for all averages reported below; SRI practices are shown in boldface. See Table 1 for key.

Treatment	Variety		Soil	
	HYV[a]	Traditional	Better	Poorer
SS/16-20/3/NPK	2.84	2.12	3.00	2.04
AS/16-20/3/NPK	4.04	2.64	5.08	2.60
SS/16-20/**1**/NPK	2.79	2.28	2.79	2.28
AS/16/20/**1**/NPK	4.01	2.89	6.07	3.15
SS/**8**/3/NPK	4.08	3.09	7.16	3.89
AS/**8**/3/NPK	5.75	3.39	8.15	4.44
SS/**8**/**1**/NPK	4.50	3.65	8.13	4.36
AS/**8**/**1**/NPK	6.62	4.29	8.77	5.00
SS/16-20/3/**C**	2.69	2.67	3.71	2.03
AS/16-20/3/**C**	4.18	3.10	6.72	3.41
SS/16-20/**1**/**C**	2.73	2.47	4.50	2.44
AS/16-20/**1**/**C**	3.82	2.88	7.45	4.10
SS/**8**/3/**C**	3.35	4.50	6.86	3.61
AS/**8**/3/**C**	4.42	4.78	9.32	5.17
SS/**8**/**1**/**C**	3.85	5.18	7.70	4.07
AS/**8**/**1**/**C**	6.83	5.96	10.35	6.39
Average difference AS>SS	**+1.61**	**+0.50**	**+2.26**	**+1.19**

[a]HYV = high-yielding variety.

Table 4. Yield differentials showing increase in yield (t ha^{-1}) associated with aerated soil compared with saturated soil. See Table 2 for key.

Treatment	Variety[a]		Soil	
	HYV[b]	Traditional	Better	Poorer
AS>SS + NPK with 16-20/3	+1.20	+0.53	+2.08	+0.56
AS>SS + NPK with 16-20/**1**	+1.31	+0.61	+3.28	+0.87
AS>SS + NPK with **8**/3	+1.67	+0.30	+0.99	+0.55
AS>SS + NPK with **8**/**1**	+2.12	+0.64	+0.64	+0.64
Average	**+1.56**	**+0.52**	**+1.75**	**+0.66**
AS>SS + compost with 16-20/3	+1.49	+0.43	+3.01	+1.38
AS>SS + compost with 16-20/**1**	+1.09	+0.41	+2.95	+1.66
AS>SS + compost with **8**/3	+1.07	+0.28	+2.46	+1.56
AS>SS + compost with **8**/**1**	+2.98	+0.78	+2.65	+2.32
Average	**+1.66**	**+0.48**	**+2.77**	**+1.73**

[a]These trials at Morondava were all on poor soils (*sable roux*). [b]HYV = high-yielding variety.

Discussion and conclusions

Three things are needed to take advantage of SRI methods: better water control; more labor, at least initially; and more skill. The practices are beneficial even without good water management, but the best results depend on maintaining aerobic soil during at least the phase of vegetative growth. We anticipate that once the greater productivity achievable with SRI methods is well documented and accepted, there will be increased investment to obtain better control over water, so that smaller amounts can be applied to rice fields in a reliable manner. For labor requirements, the Madagascar study by McHugh (2002) and Barison (2002) found that, for farmers using both SRI and conventional practices (N = 108), labor inputs were 26% higher with the SRI. However, since their yields almost doubled, farmers' returns to labor increased by more than 60%. Some farmers who have mastered the techniques in Madagascar and Sri Lanka now report that their labor inputs per hectare are lower with the SRI, so the SRI can become labor-saving over time (personal communications to author). The fact that the SRI is skill-intensive is, we think, an ambiguous disadvantage of the methodology. Increasing farmers' decision-making and management capacities should be seen as an asset rather than as a liability.

The data and analysis presented here are not intended to assert a broad claim that SRI practices currently are or will always be superior to other ways of growing irrigated rice. The methodology is relatively new, having been limited to Madagascar and a small number of farmers until the last several years. For the purposes of this symposium, we hope that readers will take away from the data and analysis not just an interest in SRI but also an interest in the possible advantages of growing irrigated rice with less water, under mostly aerobic soil conditions, the benefits thereof heightened by revised plant, soil, and nutrient management practices. We invite others to join in evaluating SRI methods and principles with the hope that farmers and countries will become able both to grow more rice with available resources and to reduce the use of water, as this becomes an increasingly scarce factor of production.

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Farmer implementation of alternate wet-dry and nonflooded irrigation practices in the System of Rice Intensification (SRI)

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Competition for limited water resources and low rice yields in developing countries have renewed interest in finding better ways to grow more rice with less water. In recent years, alternate wet-dry (AWD) and nonflooded (NF) irrigation have shown promise for reducing water consumption without a significant effect on rice grain yield. In 2001, a survey of 109 farmers was conducted in four rice-producing areas in Madagascar to investigate farmer implementation of AWD and NF irrigation as part of the recently introduced System of Rice Intensification (SRI). SRI recommends aerating the soil during the vegetative development period and transplanting young seedlings (8–12 days old) at low plant hill density (25 hills m^{-2} or fewer) and with one plant per hill. The survey showed that farmers have adapted their AWD irrigation practices to fit the soil type and their availability of water and labor. The primary drawbacks reported by farmers with implementing AWD and NF irrigation were the lack of a reliable water source, little water control, and water-use conflicts. SRI was associated with a significantly higher grain yield of 6.4 t ha^{-1} compared with 3.4 t ha^{-1} from conventional practices. On SRI plots, grain yields were 6.7 t ha^{-1} for AWD irrigation, 5.9 t ha^{-1} with NF irrigation, and 5.9 t ha^{-1} for continuously flooded. The results of the study suggest that, by combining AWD irrigation with SRI cultivation practices, farmers can increase grain yields while reducing irrigation water demand.

Historically, rice is cultivated under continuously flooded conditions in Madagascar. However, several thousand farmers throughout the island now practice alternate wet-dry (AWD) and nonflooded (NF) irrigation during the vegetative stage of crop development. AWD irrigation in this paper refers to the practice of regular cyclic flooding and drying, whereas NF includes practices by which the paddy is kept moist or saturated with no standing water. Some of these farmers practice AWD or NF irrigation in combination with conventional cultivation methods because of periodic water shortage at the beginning of the rainy season. However, many Malagasy farmers have adopted these water-saving irrigation practices as part of a new strategy of rice intensification, called SRI (System of Rice Intensification), which was developed in Madagascar in the 1980s. SRI recommends that farmers combine these new water management practices with transplanting younger (8–12-d-old) seedlings at a lower plant density (25 hills m^{-2} or fewer) and with fewer plants (one plant) per hill compared with conventional cultivation methods. The primary reason farmers apply the SRI is to increase grain yields. Farmers have reported a 50–200% increase in yield without the use of chemical fertilizers (Uphoff 1999, Vallois 1996). Water savings is a secondary motivation.

The SRI irrigation recommendation is that farmers avoid keeping their paddy soil saturated during the vegetative growth period, make efforts to introduce some soil aeration, and then maintain continuously flooded conditions during the reproductive and grain-filling stages to promote better plant growth and increase grain yield. During the dissemination of SRI, extension agents recommend to farmers that they practice either AWD or NF irrigation during the period of tillering until panicle initiation, after which they should keep the plot continuously flooded until 10–14 d before grain maturity and harvesting. In experimental trials conducted concurrently with the study reported here, this set of irrigation practices was found to require up to 55% less irrigation water than the conventional practice of continuous submergence during all periods (McHugh 2002). The productivity of water (calculated as grain yield per unit of irrigation water applied) for SRI was twice as high for AWD irrigation (0.30 kg m^{-3}) than for continuous flooding (0.13 kg m^{-3}) on the highly permeable (seepage + percolation >5 cm d^{-1}) terraced paddies used for the study.

This paper presents the results of a survey that examined farmer adaptation, grain yield, and difficulties with AWD and NF irrigation in Madagascar. Farmer implementation of these water-saving practices is compared for the cases of SRI vis-à-vis conventional cultivation methods. For more details on the SRI, see Stoop et al (2002).

Methods

A survey was conducted during the rainy season of February-June 2001 in Ambatondrazaka, Imerimandroso, Antsirabe, and Fianarantsoa with 40, 30, 28, and 11 farmers, respectively. Ambatondrazaka and Imerimandroso are located in the eastern province of Toamasina, whereas Antsirabe and Fianarantsoa are in the central highlands within the provinces of Antananarivo and Fianarantsoa, respectively. These sites are important rice-producing areas and have a significant number of farmers (but, nevertheless, a small fraction of the total population of farmers at these sites) who practice the SRI.

Farmers were selected from among those practicing both conventional (traditional) and intensive (SRI) rice cultivation. In the initial selection process, only farmers using the same rice variety for both systems were included. However, in the final number, a few farmers who used different varieties for their conventional and SRI plots (n = 7) were included in the study. The selected farmers were interviewed with a formal questionnaire about cultivation details and irrigation practices. Interviews were conducted in Malagasy by agricultural extension agents and university agronomy students during a minimum of three visits per growing season with each farmer. The interviewers were trained during pretesting of the questionnaire at each location.

Most farmers had several plots on which they practiced numerous variations of conventional and intensive rice cultivation. The survey collected agronomic and irrigation data on one selected plot cultivated with conventional practices and one with intensive practices for each farmer. The plots were selected based on meeting at least two of the three criteria for classification of conventional and intensive (SRI) cultivation, the criteria being formulated after conducting preliminary interviews. Conventional methods were transplant seedlings older than 20 d, three or more seedlings per hill, and random plant spacing. For the intensive cultivation, the criteria were transplant seedlings less than 12 d old (not including direct seeding), one plant per hill, and planting in evenly spaced rows with plants in a square grid pattern. Water management practices were thus not made a defining characteristic of either conventional or intensive cultivation, but could vary within the sample. Where farmers had more than one plot that satisfied these criteria, the interviewer selected the one considered most representative of crop growth and plot size of that farmer.

In addition to the formal interviews, grain yield was measured from 2 × 2-m quadrats during harvest time. All reported yields are calculated for paddy rice at 14% moisture content.

The general linear model analysis of variance and Tukey's simultaneous test were used to analyze the association between the farmers' irrigation practice and grain yield. These tests were chosen because they account for multiple factor variation. The analyses included geographic location, cultivation system, irrigation type, transplant age, plant hill density, plants per hill, nutrient additions or none, number of weedings, and soil type as factors that varied between plots. These factors produced a total R^2 value of 67%. Medians are reported instead of means in cases where data are highly skewed and the median better represents the average.

Results

Sites and environmental conditions

Ambatondrazaka and Imerimandroso. Both locations are in the main rice-producing plain of Madagascar around Lake Alaotra (48°43′E, 17°83′S, 750 m above mean sea level). The soils are predominantly ferruginous clayey Aquepts, Aquents, and Fluvents formed by alluvial deposits from erosion of surrounding hillsides. Inherent soil fertility is fairly poor at all locations of the survey (total N < 0.2%, Bray-II P < 10 ppm, K < 0.14 meq 100 g^{-1}) and was similar for both the SRI and conventional plots selected for the study (Barison 2002). Temperatures in the Lake Alaotra area are quite constant at 21–24 °C during the main cropping season from December to May. Rainfall amounts and distribution are very erratic from year to year. In recent years, planting has been delayed because of the late arrival of rains. Average yearly rainfall is about 1,025 mm (Fig. 1).

Imerimandroso is situated on the northeastern side of Lake Alaotra about 60 km north of Ambatondrazaka, the main town in the region, which is on the southern side

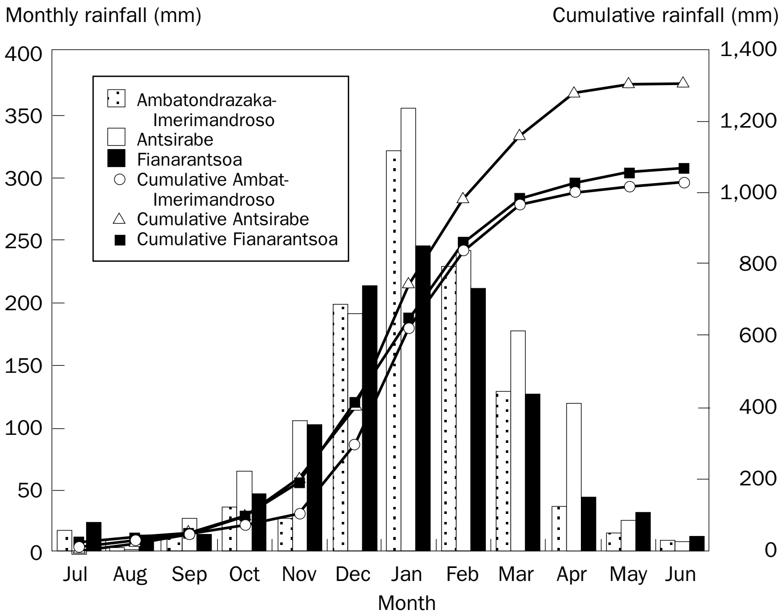

Fig. 1. Average monthly and cumulative rainfall, 1990-99.
Source: Fofifa and Centre Metéorologique d'Ampasampito.

of the lake. The area is predominantly plains, but, unlike the Ambatondrazaka area, a quarter of the study fields were situated in hilly areas.

Antsirabe. This region surrounding the large city with this name is located in the highland (*haut plateau*) of central Madagascar (the city is located at 48°03′E, 19°87′S, 1,600 m above mean sea level). Soils in the study plots are volcanic and lowland alluvium (Aquepts). The landscape is mostly hilly with a few broad valley plains. Temperatures remain fairly constant at 18–20 °C during the main rice-growing season from October until April. Yearly rainfall averages 1,310 mm.

Fianarantsoa. This region is located in the southern part of the *haut plateau* of central Madagascar (47°07′E, 21°45′S, 1,500 m above mean sea level). Soils in the study plots are Oxisols and Aquepts with high clay content. The landscape is predominantly hilly with terraced paddies. Temperatures remain fairly constant at 20–22 °C during the rice-growing season from December until May. Yearly rainfall averages 1,070 mm.

Farmer irrigation practices during crop growth

Results of the survey show that more than 80% of the SRI farmers selected for this study practice either AWD or NF irrigation. Table 1 shows the percentage of the surveyed farmers using AWD, NF, and continuously flooded (CF) irrigation during each crop growth period. The following sections summarize farmer irrigation practices during crop development.

Table 1. Percent of surveyed farmers using alternate wet-dry (AWD), nonflooded (NF), and continuously flooded (CF) irrigation during each period of crop growth.

Growth stage	Conventional			SRI		
	NF	AWD	CF	NF	AWD	CF
Nursery[a]	27	49	24	90	8	2
Vegetative[a]	1	16	83	30	53	17
Reproductive (ns)	0	5	95	2	5	93
Grain filling (ns)	0	4	96	1	6	94
Maturity (ns)	45	0	55	43	1	56

[a]Irrigation practices significantly different for conventional vs SRI ($P = 0.01$, contingency table chi-square test). ns = not significantly different at 1% level.

Seedling stage. In the conventional nursery, farmers puddle a small plot and grow the seedlings under a layer of water, which increases in depth in proportion with plant height until time to transplant. However, most of the farmers interviewed in this study no longer practice CF in their nurseries (Table 1). Farmers said that AWD and NF irrigation help with the establishment of seedlings, promote better growth, and alleviate water shortage at the beginning of the rainy season. During informal discussions, farmers in Ambatondrazaka said that they use the SRI raised-bed, nonflooded nursery to supply seedlings for all their plots when they have insufficient water or seed to maintain conventional-type nurseries. (The SRI requires fewer seedlings than conventional cultivation because of lower transplant density.)

Vegetative growth. Most of the surveyed farmers practiced AWD or NF irrigation on their SRI plots (Table 1). Seventeen percent of the farmers also practiced AWD or NF irrigation on their conventional plot. In some cases, this was due to water shortages, while in other cases farmers said that they observed better tillering and plant growth during drainage of their SRI plots, so they also adopted the practice for their conventional plots. AWD irrigation was used predominantly in the Lake Alaotra area (Ambatondrazaka and Imerimandroso), whereas NF irrigation was the most common practice for SRI plots in Antsirabe and Fianarantsoa. This regional difference in the adoption of AWD and NF irrigation is due to differences in recommendations by extension agencies and farmer preferences. When the SRI was first founded in the Antsirabe region in the 1980s, NF was the recommended type of irrigation. Over time and with the expansion of the SRI in Madagascar, extension agencies and farmers developed variations to these practices, including some recommending AWD in preference to NF irrigation.

AWD irrigation schedules varied greatly among farmers. The schedules ranged from more frequent irrigation with 1 d of flooding followed by 1 d of drying to less frequent irrigation with 10 d of flooding followed by 7 d of drying. The median AWD irrigation schedule was 4 d of flooding and then 5 d of drying, with means of 4.4 d of flooding and 4.8 d of drying. On average, the farmers who practiced the SRI in Antsirabe had a lower ratio of days flooded to days drying (1:2.4) compared with the

Lake Alaotra area (1.1:1). During informal discussions, farmers said that they developed their AWD irrigation schedule based on their own time availability, soil type, observed rice response, water availability, and recommendations from extension agents.

In the Lake Alaotra area, many farmers decide their AWD irrigation schedule based on observed soil cracking. Soils with higher clay content tend to crack faster. The differences in soil types could explain in part the large variation in AWD irrigation schedules. Some SRI experts have recommended that farmers flood their plots every night and drain them the next morning. However, this study did not find any farmers implementing this schedule. During informal discussions, farmers said that the amount of labor required to irrigate and drain daily makes that schedule impracticable. Farmers developed their own irrigation schedules that they believed produced the best rice growth and fit their labor and water availability.

Nonflooded irrigation (NF) was practiced on most of the SRI plots in Antsirabe and Fianarantsoa. Farmers said that they kept their soil moist or saturated with no standing water during the vegetative growth period. Moist soil conditions were maintained by passing water through the paddy without building up a layer of water. One farmer controlled soil moisture with a peripheral ditch around the edge of the paddy. This enabled him to regulate soil moisture by supplying and draining water from the peripheral ditch. Although this practice has been recommended by SRI experts, we found only one farmer implementing it.

Reproductive and grain-filling stages. Continuously flooded (CF) irrigation was practiced by more than 90% of the farmers during the reproductive growth and grain-filling stages on both SRI and conventional plots (Table 1). Farmers said that these are the periods when the rice plant “needs the most water” and that it is essential to keep a layer of water on the paddy to produce high grain yield. Some farmers were not able to maintain flooded conditions because of a lack of water availability and/or long water-sharing rotations.

Grain maturity. Irrigation practices during grain maturity (yellow ripening) were similar for both conventional and SRI plots. Farmers prefer to dry their plots during this period to homogenize grain ripening. However, it is not always possible because so much irrigation is plot-to-plot. In this type of setup, all available land area is placed in production with minimal or often no space saved for irrigation and drainage channels. Because of differences in planting time and rice variety, it is not possible for the rice in all the plots of the irrigation chain to reach maturity simultaneously. To maintain flooded conditions for plots that have not yet reached maturity, all the plots in the irrigation chain remain wet or flooded.

Cultivation practices

A large variation occurred in cultivation practices between farmers and between locations (Table 2). A comparison of practices by location shows similarities between Ambatondrazaka and Imerimandroso in the Lake Alaotra area and between Antsirabe and Fianarantsoa in the highlands. This was expected because of similarities in altitude, environmental conditions, landform, and geographic location. As seen in Table 2, more variation occurred in conventional practices between locations than for the

Table 2. Farmer cultivation practices.

Cultural details	Ambatondrazaka		Imerimandroso		Antsirabe		Fianarantsoa		Overall mean		
Cultivation system (sample size, no. of farmers)	SRI (40)	Conv. (40)	SRI (30)	Conv. (30)	SRI (28)	Conv. (28)	SRI (11)	Conv. (11)	SRI (109)	Conv. (109)	Difference (109)
% who applied fertilizer within past year	3	0	0	0	18	21	64	18	12	7	5
% who applied manure/compost within past year	10	5	0	3	46	64	73	18	23	21	2
Age of transplant (DAS)[a,b]	9–11	26–31	9–11	29–33	9–12	41–48	7–13	18–33	10	33	20–26**
Average plant hill density m^{-2}	26	44	26	42	18	35	24	30	24	40	11–21**
Average seedlings per hill[c]	1	3.3	1	3.5	1	2.8	1	2	1	3	1.9–2.3**
Median number of times weeded	2	1	2	0	4	2	2	1	2.7	1.2	1.2–1.8**
% who applied herbicide	38	48	0	93	0	0	0	0	16	48	32*
% cultivating off-season crops within past 3 years	10	8	0	0	71	82	73	27	29	27	2

[a]Days after seeding pregerminated seeds. [b]95% confidence interval for mean. [c]All farmers used 1 seedling per clump in SRI practice except for one farmer in Antsirabe who used an average of 2.5 seedlings per clump. * = difference significant at $P = 0.05$; chi-square test with contingency table. ** = 99% confidence interval for difference in means; paired t-test.

intensive (SRI) practices. This can be expected because SRI practices were recently introduced into these areas and they have not had sufficient time for farmer modification and adaptation to differences in climate, soils, and socioeconomic conditions. In this study, the average farmer experience with SRI was 2.3 years compared with an average of 16 years' experience with conventional rice cultivation.

On average, the conventional cultivation practices for farmers in this study consisted of transplanting 33-d-old seedlings with 3 plants hill^{-1} and 40 hills m^{-2}, and one weeding during the season. Plots with SRI practices had younger transplants (10 d old), fewer plants per hill (1), fewer hills per unit area (24), and more weedings (2–3) during the season compared with the conventional plots. There was no significant difference in the number of farmers applying nutrients and growing off-season crops on their SRI plots compared with the conventional plots (Table 2).

The SRI method of cultivation recommends application of compost and manure rather than chemical fertilizer. This study found, however, that only a quarter of farmers who practice SRI were applying any nutrients to their fields; five farmers in Antsirabe, seven in Fianarantsoa, and one in Ambatondrazaka used fertilizers while 25 used cattle manure and/or compost with their SRI crop. Most of the farmers applied the nutrients to their off-season crop and not directly for their rice crop. The common off-season crops were potatoes, beans, garden vegetables, and wheat. Over half of the surveyed farmers used chemical herbicides for weed control in the Lake Alaotra area. Farmers in this study used 13 different rice varieties, mostly improved indica varieties and some japonica varieties. All except seven of the farmers used the same variety for both their conventional and SRI plots. The difference between conventional and SRI plots is the same no matter what variety is used.

On average, farmers allocated 29% of their total cultivated rice area (average total area per farmer was 0.8 ha) for SRI practices. The difference in area cultivated with SRI and conventional practices could be due to the relative inexperience of farmers with the more recently adopted SRI practices. The high labor demand and higher risk associated with SRI may also limit the area that farmers can afford to cultivate (Barison 2002, Moser 2001).

Grain production

Analysis of grain yields indicated a large difference between the conventional and SRI plots (Table 3). The overall average SRI yield of 6.4 t ha^{-1} was significantly higher at the 1% level (paired t-test) than the 3.4 t ha^{-1} observed on conventional plots. At all locations, grain yields for SRI were 70–90% higher than conventional yields. The mean yield of 3.4 t ha^{-1} with conventional practices for farmers in this study is considerably higher than the national average of 2.03 t ha^{-1} for paddy rice in Madagascar (mean for 1998-2000, FAO 2000). This indicates that the farmers selected for this study who have adopted SRI and the water-saving practices of AWD or NF irrigation are above average in their skills, their means of production, or possibly their soil quality.

Table 4 presents the grain yields measured according to AWD, NF, and CF irrigation at each location. For yield analysis, plots were categorized as AWD, NF,

Table 3. Mean grain yield for conventional vs intensive practices (t ha^{-1} paddy rice).

Location	Conventional grain yield	SRI grain yield	Difference in yields[a]
Ambatondrazaka	3.4	6.7	2.4–4.2
Imerimandroso	3.4	6.7	2.8–3.8
Antsirabe	3.2	5.5	1.5–3.1
Fianarantsoa	3.4	6.3	1.3–4.6
Overall mean	3.4	6.4	2.6–3.4

[a]99% confidence interval for difference in means; paired t-test.

Table 4. Summary of yields by irrigation practice[a] and by location (t ha^{-1}).

Location	Conventional plots			SRI plots		
	CF	NF	AWD	CF	NF	AWD
Ambatondrazaka	3.38 (36)[b] 0.48[c]	–	3.79 (3) 0.40	6.40 (9) 2.2	5.44 (9) 1.7	7.37 (21) 1.9
Imerimandroso	3.38 (16) 0.50	–	3.46 (14) 0.41	6.15 (1) 0	–	6.74 (29) 1.2
Antsirabe	3.23 (27) 0.57	2.38 (1) 0	–	5.61 (7) 1.4	5.62 (13) 1.9	5.12 (8) 1.4
Fianarantsoa	3.38 (11) 0.39	–	–	3.00 (1) 0	6.69 (10) 1.4	–
Overall mean[d]	3.34 a (90) 0.50	2.38 a (1) 0	3.52 a (17) 0.42	5.89 ab (18) 1.9	5.91 a (32) 1.8	6.74 b (58) 1.6

[a]Irrigation treatments are based on the irrigation practices during vegetative growth. [b]Sample size, number of farmers. [c]Standard deviation [d]Yields followed by different letters are significantly different at 5% level.

and CF irrigation based on the irrigation practice during the vegetative stage of crop development. Vegetative growth is the longest period during rice development and the main period when SRI irrigation differs significantly from conventional irrigation (Table 1). The plots with AWD irrigation produced the highest average yield in both the conventional and SRI plots. The highest mean yield of 7.4 t ha^{-1} was produced with AWD irrigation and SRI cultivation practices in Ambatondrazaka. In the case of Antsirabe, AWD irrigation produced a lower mean yield than both CF and NF irrigation, however. This difference from what was observed at the other locations could be due to the soil type or difference in AWD irrigation frequency (discussed above). For the SRI plots, the overall average grain yield for AWDI (6.7 t ha^{-1}) was significantly higher at the 5% level than for the NF plots (5.9 t ha^{-1}). However, because of the relatively small sample size and the high variation in farmer yields (see Table 4), the mean CF yield was not statistically different from that of AWD or NF irrigation. For the conventional plots, there was no significant difference in yields among CF, NF, and AWD irrigation.

Table 5 presents the statistical analysis of the combined grain yields for both conventional and SRI cultivation to look at the effects, ceteris paribus, of the different variables measured. The results indicate that cultivation system, geographic location, and soil type account for 28%, 12%, and 9%, respectively, of the overall variation in yields. Irrigation type during vegetative growth, nutrient additions or not, and transplant age were the important management factors accounting for 5%, 4%, and 3%, respectively, of the overall variation in grain yields. The other management factors (plants per hill, plant hill density, and number of weedings during the season) did not have any statistically significant association with the grain yields. These results suggest that the difference in SRI and conventional yields is not due to any one management factor but is the result of a synergistic (collective) effect of SRI practices. There were no statistically significant interactions between the main factors. However, at $P = 0.07$, there was an interaction between cultivation system and soil type. Conventional yields were relatively constant for all soil types, whereas SRI produced higher yields on clayey and organic soil than on loamy and sandy soil. A similar interaction was observed for irrigation and soil type. CF yields were constant for all soil types while AWD and especially NF irrigation yields were higher for clayey and organic soil compared with loamy and sandy soil, which produced the lowest yield. Although statistically insignificant, these results suggest that there should be further research on the effects of soil type on SRI yields.

Table 5. General linear model statistical analysis of grain yield for all plots, all locations.

Factor	Adj SS[a]	Adj MS[a]	F	*P* value
Cultivation system (SRI vs conventional)	47.796	47.796	31.65	<0.001
Geographic location	20.005	6.668	4.42	0.005
Irrigation type	9.440	4.720	3.13	0.046
Soil type	16.345	4.086	2.71	0.032
Nutrient additions	6.965	6.965	4.61	0.033
Transplant age	6.302	6.302	4.17	0.043
Plants per hill	0.220	0.220	0.15	0.703
Plant hill density	0.145	0.145	0.10	0.757
Number of weedings	8.508	1.215	0.80	0.584

[a]SS = sum of squares, M = mean squares.

Discussion

Considerations for farmer adoption of alternate wet-dry and nonflooded irrigation

The infrastructure and labor requirements for AWD and NF irrigation present difficulties for wide-scale adoption by farmers in Madagascar. In this study, 37% of the farmers said that they have difficulties with AWD and NF irrigation (Table 6). It is important to note that this percentage is probably lower than for the population as a whole since only farmers who are practicing SRI and thus are more likely to have the necessary conditions for its implementation were included in the study. Some of the special requirements for wide-scale adoption of AWD and NF irrigation include a reliable water source, good water control, good social structures for water sharing, and available labor.

Reliable water source. Unreliable water source was the most common problem reported by farmers in the survey (Table 6). With AWD irrigation, plots are drained and left to dry with the assumption that water will be available when needed at the end of the drying period. However, as seen in Table 7, most of the farmers in this study rely on stream flow as their irrigation source. At the beginning of the rainy season, which is during the vegetative growth period, stream flow is not reliable because of irregular rainfall, low base flows, and high demand for water for land preparation and crop irrigation. Farmers in Antsirabe and Fianarantsoa reported long periods when there was insufficient water to meet irrigation demand. This could be expected considering that more than 75% of the farmers in those locations depend on direct rainfall and small stream flow for irrigation (Table 7). Construction of water-storage devices is a possible means for creating more reliable water supplies.

Water control. Lack of water control is another factor that prevents implementation of AWD and NF irrigation in many parts of Madagascar. Large areas around Lake Alaotra are susceptible to flooding because of a seasonal increase in the water level of the lake and erosion and siltation of drainage canals. The broad valley plains

Table 6. Problems that farmers reported with applying SRI water management (AWD or NF irrigation).

Location	Do you have difficulties with SRI water management? % (yes)	Listed reasons[a]		
		Little water control[b] %	Unreliable water source %	Conflict in water use[b] %
Ambatondrazaka	43	18	65	6
Imerimandroso	7	50	50	0
Antsirabe	46	8	31	61
Fianarantsoa	73	38	62	38
Total average	37	20	53	30

[a]Reasons given by farmers who say they have difficulty with SRI water management. [b]Includes both irrigation and drainage.

Table 7. Irrigation source characteristics for farmers in the study.

Location	Type of irrigation source (% of farmers in study)				Farmers with water shortage (%)	Duration of period of water deficit[a,b] (days)	Months of water deficit[a]
	Stream	Dam	Reservoir	None[c]			
Ambatondrazaka	47	47	3	3	45	30–41	Dec, Feb-Mar
Imerimandroso	60	30	10	0	30	0–31	Oct-Dec
Antsirabe	85	7	4	4	25	33–128	Oct-Dec, Mar
Fianarantsoa	23	13	14	50	82	31–44	Oct-Nov, Jan-Feb
Total average	54	24	8	14	45	37	

[a]Period during main rice-growing season when water shortage is common. [b]95% confidence interval for median. [c]Irrigation from rainfall and direct drainage from other paddies that receive irrigation from rainfall.

and valley bottoms of Antsirabe and Fianarantsoa are also susceptible to seasonal flooding. Eight of the farmers practicing SRI in this study reported a lack of water control as a difficulty. This number is relatively low because the localities selected for this study did not have the flooding problems experienced by many of the neighboring communities. Infrastructure needs to be built to control flooding and to permit drainage of Madagascar's major rice-producing areas before AWD or NF irrigation can be widely adopted.

Water sharing. A large percentage of farmers in Antsirabe and Fianarantsoa reported a conflict over water use as a difficulty with AWD and NF irrigation (Table 6). More than 60% of the plots in Antsirabe and Fianarantsoa are hillside terraces. Conventional irrigation for these is by cascade irrigation where water flows directly from plot to plot. This often leads to conflicts of interest in water management. Good social organization and/or construction of irrigation and drainage channels that allow for independent irrigation and drainage of individual plots are necessary to successfully implement AWD and NF irrigation in such situations. Installation of irrigation and drainage channels in the hillside system could change the dynamics of the system because the sequential water-storage function of flooded paddies in plot-to-plot irrigation will be modified. Construction of on-farm reservoirs and coordination among farmers of the timing of flooding and drainage cycles are possible solutions to this problem.

Labor requirements. It is worth noting that farmers did not list labor shortage as a primary difficulty with AWD or NF irrigation. However, labor availability was a significant factor affecting farmers' decisions about the frequency of drying and flooding. With traditional continuous flooding, farmers in most cases simply adjust the outlet vane height to the desired flood depth and do not have to devote much time to irrigation after the beginning of the cropping season. However, AWD irrigation requires that the farmer adjust and readjust the vane height to drain and irrigate on a regular basis. This can require a significant amount of labor depending on the number of plots that a farmer owns and how far apart the plots are from the farmer's home. NF irrigation may require even more frequent adjustments.

Another labor consideration for AWD and NF irrigation is the extra weeding operations needed to control weed growth when there is no continuous flooding. CF is widely used to suppress weed growth. In Table 2, SRI cultivation was associated with an average of one to two more weeding operations during the season compared with continuous flooding. The labor required for the additional weeding operations could be difficult for farmers to commit during periods of labor shortage (for more information on SRI labor constraints, see Moser 2001). Farmers need to take this into consideration when implementing AWD or NF irrigation. For the farming operations covered by this study, Barison (2002) determined that the extra labor and costs for SRI compared with conventional cultivation are more than compensated for by the higher yields.

Conclusions

A survey of 109 farmers was conducted at four locations in Madagascar to explore farmer irrigation practices for conventional and intensive systems of rice production. Information was collected during formal and informal farmer interviews. Grain yield was also measured from one conventional and one SRI plot of each farmer. Results of the study revealed a wide variety of irrigation practices of farmers. With an average of 2.3 years of experience with alternate wet-dry and nonflooded irrigation, farmers have adjusted their irrigation schedules to fit their particular conditions.

Farmers base their irrigation schedule on many factors, including crop response, soil type, and water and labor availability. Farmers reported a lack of a reliable water source as the primary difficulty with practicing AWD or NF irrigation. Inabilities to control water and conflicts over water use were also reported by many farmers. There was a significant association between irrigation practice and overall grain yields as AWD irrigation produced higher grain yield than NF irrigation, while continuous flooding was not significantly different from AWD or NF irrigation.

Some of the solutions for wider-scale adoption of AWD irrigation offered in this paper included developing more effective structures for water sharing, constructing irrigation and drainage channels, installing on-farm reservoirs, and building infrastructure for flood control. The 2–3-t ha^{-1} increase in grain yield observed in this study when AWD irrigation is practiced in combination with SRI cultivation methods may justify these financial investments.

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Notes

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The System of Rice Intensification in practice: explaining low farmer adoption and high disadoption in Madagascar[1]

C.M. Moser and C.B. Barrett

The System of Rice Intensification (SRI) has received a fair amount of attention in recent years both in and outside of Madagascar, where incredible yield increases have been achieved using few external inputs and less water and seed than conventional rice production systems. SRI initially seemed well suited to Madagascar because of the unavailability or high cost of fertilizer and the inability of most farmers to grow enough rice to feed their families. Despite the promise of this technology, farmer adoption of SRI in the areas where it was promoted has been low, "disadoption" (abandonment) of the method has been high, and those who continue to practice the method rarely do so on more than half of their land.

To help explain this phenomenon from an economic perspective, a study was conducted in five communities in Madagascar in 2000, using both participatory research methods and a household survey of more than 300 farmers. Based on the study, we find that SRI is difficult for most farmers to practice because it requires significant additional labor inputs at a time of the year when liquidity to hire labor is low and family labor effort is already high. Thus, the poorer the farmers and the more their income depends on rainy-season crops, the less able they are to take advantage of the technology. The results point to the challenge facing researchers and policymakers concerned with the promotion of water-saving rice technologies: even when yields can be increased while saving water, adoption by farmers is still far from assured.

[1]Adapted from the paper "The Disappointing Adoption Dynamics of a Yield-Increasing, Low External-Input Technology: The Case of SRI in Madagascar" (Moser and Barrett, *Agricultural Systems,* forthcoming).

The System of Rice Intensification (SRI), developed in Madagascar with the help of Malagasy farmers, seemed to be particularly well suited to the needs of Malagasy farmers. The method requires no chemical fertilizers or pesticides and can be practiced with local seed varieties. Thus far, SRI yields seem to be sustainable, and it was hypothesized that intensifying lowland rice production would reduce the clearing of land for upland rice production responsible for a significant part of the deforestation in Madagascar. Most importantly, the method has been repeatedly shown to double or triple rice yields in smallholder farmers' fields (albeit from a low base with average yields of 2 t ha^{-1} or less).

Despite its obvious benefits and intensive extension efforts by an indigenous nongovernmental organization (NGO), SRI has not taken off as expected. As we document below, we find that adoption rates have generally been low, the average rate of disadoption (the percentage of households that have tried the method but that no longer practice it) has been high, at 40%, and those who adopt and retain the technique rarely put more than half of their rice land under SRI. Although many field observers suggest that peasant resistance to new approaches may explain the observed patterns, the explanation for the disappointing adoption dynamics of SRI seems to revolve around the oft-overlooked distinction between cash expenditures and opportunity cost, the importance of timing in determining opportunity cost in economies plagued by weak financial systems, and the implications of resource opportunity cost for smallholder investment choice.

SRI requires few external inputs, and thus minimal cash outlays on seed, chemical inputs, or machinery. Nonetheless, for many Malagasy rice producers, SRI requires intense labor effort at just the time poorer farmers must go work others' fields for wages to earn cash to meet immediate consumption requirements. Since wages are the primary source of cash in the absence of interseasonal credit, the opportunity cost of labor is simply too high to justify adoption for many. When weak rural financial systems drive up the implicit interest rate on (nonexistent) interseasonal credit, even the net present value of sharp yield gains may compare unfavorably with unskilled farm wages today, so smallholders rationally choose not to invest in SRI. Widespread disadoption of SRI, especially by those with salaried employment for whom the opportunity cost of labor is likewise high, seems to underscore the importance of labor intensity in explaining the adoption patterns for SRI. This case study thereby raises several broader questions about other water-saving rice technologies, especially those that are labor-intensive but do not offer the yield increases of SRI.

After a brief explanation of the Malagasy context, SRI, and the data used in this study, we explore the patterns of SRI adoption, paying particular attention to the dynamics of adoption, the role of extension, and which farmers successfully practice the method. A more technical treatment of adoption, extent, and disadoption decisions can be found in Moser and Barrett (2002). Finally, we bring the first points together to explain the role of severe seasonal liquidity constraints to technology adoption and what this implies for both SRI in Madagascar and water-saving rice technologies in general.

Data and survey sites

Over several months in early 2000, we explored the determinants of SRI adoption in five purposively selected communities that each had at least five years' exposure to SRI. We first undertook qualitative research using rapid rural appraisal techniques, such as the construction of seasonal calendars and enumeration of prevailing livelihood strategies. Then we collected household-level survey information on individual farmers' history of SRI practice from 1993 to 1999. Two of the sites, Manandona and Anjazafotsy, are in the central highlands region of Antananarivo, near the city of Antsirabe. Antsirabe is characterized by relatively good transportation systems and well-developed markets, including several food-processing factories that buy local milk, wheat, and barley, among other crops. Thus, market access for both Manandona and Anjazafotsy is excellent by Malagasy standards, and rice-growing practices are more advanced in this region than in the other villages of the study. The other three villages of this study, Ambatovaky, Iambara, and Torotosy, are near the Ranomafana National Park on the island's eastern escarpment in Fianarantsoa Province, the poorest region of Madagascar. Of the three villages, Ambatovaky has the best market access, being one hour by vehicle from a local weekly market. The other two villages are several hours by foot from the nearest market or road.

We performed a census in each village to enumerate precisely the numbers of adopters, disadopters, and nonadopters. Households were then randomly selected from each of these three strata—adopters, disadopters, and nonadopters—for an overall sample size of 317 households. Knowing the precise number of adopters, disadopters, and nonadopters in each village allows us to correct for choice-based sampling bias common in adoption studies. The questionnaire covered farm and household characteristics, such as landholdings, family size, age and education of the household head, and major sources of income, as well as the history of SRI use, details of SRI and non-SRI practices, and problems encountered with the method. Farmers were asked to recall total rice area and the proportion of that area under SRI for the period 1993-99. Given the importance of rice land to the household and supported by extension records, these recall data are considered quite reliable. Because income sources, rather than actual measures of income or food stocks, are used in this study, we can only make rather loose inferences here. We believe that this method of evaluating and categorizing income sources in each village based on their seasonality and significance using extensive interviews and participatory research, while not statistically rigorous, provides reliable indicators of household wealth and liquidity.

SRI in Madagascar

Although rice accounts for approximately 44% of the land under cultivation and nearly 50% of caloric intake in Madagascar (FAO 1998), most farmers cannot produce enough rice to feed their families. Seasonal price fluctuations place a further burden on net buyers of rice, a group that includes a sizable majority of Madagascar's rice farmers (Barrett and Dorosh 1996, Minten and Zeller 2000). Total rice production increased little in the country during the 1990s and yields were stagnant and well below world average yields (IRRI 2000). Because of the importance of rice for both family income and nutrition and because of the significant role that upland rice cultivation plays in deforestation in Madagascar, intensification of lowland rice production has been a major focus of many development interventions.

The System of Rice Intensification is a method that has been promoted and closely followed in Madagascar for more than ten years. It was developed in Madagascar in the late 1980s by a French priest working with Malagasy farmers, who later formed the NGO Association Tefy Saina (ATS) to promote the method. SRI consists of five recommended practices: early transplanting, the planting of single seedlings, wide spacing, intermittent irrigation and good water control, and frequent weeding. The application of compost is also recommended because of the low soil fertility and high cost of chemical fertilizers in Madagascar, but ATS does not consider this a requirement. Some of the individual components, such as adequate spacing and weeding, are commonly recommended practices for rice cultivation (Grist 1975, Vergara 1994). However, SRI's remarkable yield increases seem to be achieved only when all of these practices are used in combination. The relative importance and contribution of each of the individual components of the system are currently being studied and there does appear to be a synergistic relationship among the components.

With traditional methods, farmers transplant seedlings 30 to 90 d old in hills of 3 to 5 plants spaced close together. The older seedlings are considered hardier and close spacing reduces weed growth. With SRI, transplanting of individual plants 7 to 15 d old spaced at least 25 cm apart is recommended. Farmers report that handling and transplanting these young plants are initially difficult and time-consuming.

Good water control and the minimal use of water are both among the most controversial and promising aspects of SRI from a crop-science perspective. From the farmer's perspective, this is also one of the more difficult parts of the system to master. Contrary to most lowland rice-growing practices in Madagascar and throughout the world, the SRI field is not continuously flooded and is instead treated with intermittent irrigation, usually a form of alternate wetting and drying. It has been speculated that drying the fields allows for good aeration of the soil and better root growth. McHugh et al (2002a) found that SRI under alternate wetting-and-drying irrigation used 19–55% less water than conventional lowland rice, depending on the permeability of the soil.

To achieve the necessary level of water control, a level field and a functioning irrigation system offering the ability to let water in and out of the field as needed are essential. Unfortunately, these conditions are rarely met in Madagascar. According to Rakotonjanahary (personal communication, 2002), adequate water drainage—only possible on an estimated 20% of rice area in Madagascar—is the major limiting technical factor to SRI in Madagascar.

The combination of wide spacing and less water use in SRI provides ideal conditions for weed growth, which means that frequent weeding is necessary. The few studies of its labor requirements show that SRI requires an estimated 38% to 54% more labor than traditional methods (ATS 1995, Rakotomalala 1997). According to

Rakotomalala, 62% of the extra labor needed for SRI is for weeding and 17% for transplanting. Hired labor is generally available during the rice-growing season in Madagascar, as the landless and land-poor seek wages to make it through the hungry season. Even under traditional methods, most households hire labor for larger tasks such as transplanting, weeding, and harvesting.

Even with the additional costs, the returns to labor still seem to far outweigh those of traditional methods. Average lowland rice yields for traditional methods vary from region to region, but are generally from 2 to 3 t ha^{-1}. Several studies have simultaneously recorded yields for both SRI and non-SRI fields. In the Ranomafana region, Rakotomalala (1997) found average SRI yields of 6.19 t ha^{-1}, while traditional methods yielded only 1.95 t ha^{-1}. A 1998 study in the Menabe area of western Madagascar found the difference in on-farm yields to be smaller—4.3 t ha^{-1} for SRI versus 3 t ha^{-1} for traditional systems. A 2000 research center trial by Rajaonarison in this same region found SRI yields of 6.83 t ha^{-1} and "conventional" yields of 2.84 t ha^{-1}. Individual farmer SRI yields of more than 10 t ha^{-1} have regularly (and credibly) been reported. Given this performance, SRI has understandably created widespread interest in other rice-growing regions of the world, with recent, largely successful, on-farm trials in at least ten countries (Uphoff 2000). Yield data were not collected in this study. However, based on a limited number of disadopters for whom we have past SRI yield records from ATS, there does not seem to be a significant difference in yields between farmers who later disadopt and those who continue. Furthermore, disappointment with SRI yields was not cited as a reason for disadoption by a significant number of farmers.

Adoption patterns and farmer perceptions

Prior to this study, the data collected in Madagascar on SRI were mostly limited to summaries of the number of adopters, area under SRI, and SRI yields (ATS 1995, 1998, 1999, Association-Tefy-Saina-Fianarantsoa 1999, Andrianmiarsonarivony 1999). Research on SRI focused mainly on agronomic questions in order to document and explain the incredible yields being achieved (Hirsch 2000, Uphoff 1999). Although it was clear that some farmers were disadopting, little was known about the rates of and reasons for disadoption or about the farmers who were successful with the method. This information is crucial for assessing claims that the technology would greatly benefit poor smallholder farmers but, perhaps surprisingly, is commonly absent from studies of new technologies (Lee and Ruben 2000).

Adoption rates and dynamics

We start by looking at simple descriptive statistics of SRI adoption rates across sites and households. The extensive literature on the adoption of agricultural technologies has long emphasized the importance of education, extension, income, and wealth as determinants of propensity to adopt, timing of adoption, or both (Feder et al 1985). Our results echo those patterns, as we describe below. Far fewer studies have examined either patterns of disadoption (Carletto et al 1996, Neill and Lee 2001) or adoption dynamics at the household level (Foster and Rosenzweig 1995, Cameron 1999, Conley and Udry 2000).

Failure to take disadoption seriously signals an implicit assumption that new technologies are unambiguously superior to older ones, or that farmers do not adopt so as to experiment with a new practice, either of which implies irreversibility of the adoption choice. Such assumptions are plainly unwarranted in the case of SRI in Madagascar, where the percentage of farmers trying SRI who disadopted was surprisingly high, ranging from 19% to 100% across the five sites (Table 1). Although both groups of farmers have revealed their preference not to use the technology under current conditions, the decision to disadopt a technology one has tried plainly differs from the decision not to adopt initially. Differences in the characteristics of disadopters and nonadopters therefore provide a window into understanding the obstacles to initial adoption of a technique. Similarly, comparison between adopters and disadopters, both of whom were obviously able to try the new technology, conveys information on those features of the technology that prove unappealing to at least some farmers under prevailing field conditions.

Working with both farmers and extension agents, we reconstructed the history of SRI adoption for all farmers at each site to provide a clear picture of the trends in adoption and disadoption over time. Besley and Case (1993) proposed this approach of using recall data in adoption surveys to correct for the bias inherent in traditional cross-sectional studies because of analysts' inability to differentiate between late adopters of the technology and those who will never adopt. Figure 1 plots the number of adopters and disadopters from 1993 to 1999 across all five sites. Each year, a few more farmers tried SRI at each site, thereby expanding the base of adopters steadily. By the second year, however, a few farmers were already dropping SRI, although the sharpest increase in disadoption occurred in 1999 for Ambatovaky, Iambara, and Torotosy, when funding interruptions for ATS temporarily disrupted extension support. Disadoption was more gradual in Anjazafotsy, where extension has been continuous, yet the overall rate of disadoption is similar to that of the other sites (Table 1). Manandona had both the highest percentage of households adopting and the lowest rate of disadoption. These patterns raise important questions as to the characteristics of adopters, disadopters, and nonadopters.

Table 1. SRI adoption and disadoption patterns.

Item	Ambatovaky	Iambara	Torotosy	Anjazafotsy	Manandona	Av[a]
% households trying the method, 1993-99	48	16	27	28	21	25
% households using the method in 1999	26	7	0	13	17	15
% adopters who later disadopted	46	53	100	49	19	40

[a]Average is weighted to account for different numbers of households at each site.

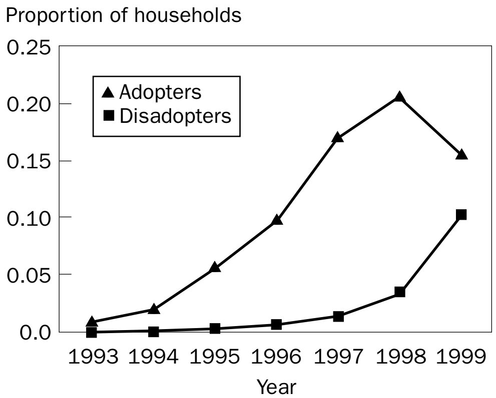

Fig. 1. The evolution of SRI adoption, 1993-99.

Extension

Most farmers in the study area learned SRI from ATS extension agents. Sixty-six percent of the adopters learned either through training or by working with an extension agent or local expert and only 30% reported learning from other farmers. As already mentioned, there was a large increase in disadoption for three of the sites, corresponding to the temporary disruption of extension services in 1999. This suggests that extension support is critical for this technology well beyond the period of initial introduction. Put differently, one might expect new adoption to fall off in the absence of extension training, but the decline in SRI use by established users is a bit more puzzling.

One possible explanation is that this underscores how complex the method really is for farmers accustomed to transplanting sturdy rice seedlings, closely spaced, and grown in standing water. Another, perhaps complementary explanation, is that because SRI marks a radical break from traditional methods, there is cultural resistance to it that is overcome only by the presence of extension advocates because of the respect for authority that pervades Malagasy culture. Either way, the apparent extension-intensity of SRI promotion raises serious questions about the financial feasibility of scaling up SRI use.

Farmer practices and perceptions

The household survey included questions on both the SRI and non-SRI practices of farmers. The first interesting thing to note is that, although SRI is a set of techniques, farmers seem to adopt all of them (except composting) with little adaptation. Furthermore, farmers who try SRI but subsequently disadopt do not seem to alter former practices after using SRI. In sum, many farmers don't seem to "learn" from their experience with the method, as might be manifest by widespread adaptation or selective retention of constituent practices postdisadoption. This is despite claims by ATS that their farmer training programs encourage experimentation and emphasize teaching farmers about the needs of the rice plant.

Questions were asked regarding farmers' decisions to practice or not to practice SRI. Nonadopters were asked why they did not practice the method, disadopters were asked why they no longer practice the method, and adopters who did not have all of their rice land in SRI were asked why they did not expand their SRI holdings. Multiple responses were possible and these are reported in Table 2. Lack of time and money were among the most frequently cited reasons for all farmers. Extension was an important reason cited by nonadopters and disadopters for not practicing the method.

Irrigation and other problems related to water control have long been assumed to be major obstacles to SRI adoption, and although a significant number of farmers found water control problematic, it was clearly not the most important problem at our survey sites. This is possibly because ATS selected sites for SRI promotion partly based on water management potential. Unfortunately, this means that we are unable to examine the water management problems properly in this study. A study conducted at four sites in Madagascar found that the most common problems related to water control for SRI were the lack of a reliable water source, the lack of water control, and water-use conflicts (McHugh et al 2002b)

Because we simply asked farmers their perceptions of problems or obstacles, we have no objective measure of irrigation type or quality in our survey. We can categorize the water management problems concerning SRI by the type of labor investment required. First, farmers must be able to let water in and out of their fields as needed. Depending on the irrigation system, an individual farmer may be powerless to alter his field's condition. In some cases, however, it may also be possible that the farmer can achieve adequate water control through minor improvements in the irrigation ditches and drains surrounding his field.

The second water management problem is that an SRI field must be level so that a small amount of water will be distributed evenly. Thus, the amount of work needed to achieve this requirement obviously depends on the original state and size of the field. These first two water management problems generally must be overcome before practicing SRI. It is not known to what extent these initial investment costs are a barrier to SRI adoption. Seventy-six percent of the adopters reported initial investment costs of water control or field preparation (especially leveling), but nonadopters rarely cited water management specifically as a problem.

Table 2. Obstacles to practicing or "fully" adopting SRI (proportion of respondents citing a particular obstacle).

Obstacle	Adopters	Disadopters	Nonadopters
Lack of money	0.41	0.36	0.34
Lack of time	0.33	0.43	0.21
Lack of materials	0.24	0.25	0.28
Lack of fertilizer	0.22	0.20	0.18
Lack of extension or training	0.05	0.20	0.23
Water control problems	0.36	0.11	0.21

The third water management problem concerns the daily inspection of the water level. With traditional methods, farmers can be absent from their fields for a week or more at a time. For time-constrained farmers or for farmers with distant fields, daily trips to the field(s) may be difficult. In addition, in many parts of Madagascar, it is common to own several small, widely dispersed parcels, which implies that it might be difficult to practice an intensive method, such as SRI, on all of them. Indeed, we found that the distance between farmers' rice fields reduces the proportion of their land in SRI (Moser and Barrett 2002).

Scale of practice

Given the nontrivial fixed costs of land leveling and ongoing water management, there would seem to be some economies of scale to be gained from trying SRI over larger parcels, rather than just a fraction of a hectare, as is the norm. Indeed, several ATS field agents expressed concern that trying SRI on a very small area makes the method unprofitable and leads to disadoption. If this were true, we would expect to see differences in the area cultivated in SRI between adopters and those who eventually disadopted with the same years of experience in SRI. Figure 2 shows this to be precisely the case. In their first year with the technique, those who continued to use SRI cultivated both a larger share and a 72% larger area (a mean of 0.197 ha versus 0.115 ha) than did those who later disadopted. Fifty-three percent of the disadopters practiced the method for only one year, and 10% practiced it for four or more years.

As farmers gain experience with such a seemingly profitable method, one might expect to see increases in the area cultivated under SRI. But, as Figure 2 suggests, the expansion in SRI area proved relatively modest for most farmers. For both adopters and disadopters, the proportion of land in SRI levels off after three to four years of experience to 43% and 39%, respectively. Among ongoing users, average area in SRI increased from an average of 0.20 ha in their first year of use to only 0.24–0.27 ha in years two through five, after which our sample size is too small (less than ten farmers) to provide meaningful inference. Only 12 of 163 households surveyed that tried

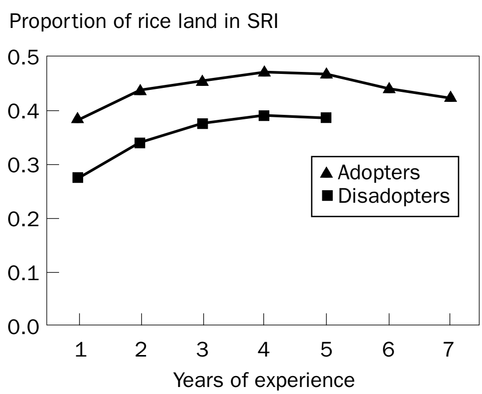

Fig. 2. Proportion of land in SRI by years of experience.

SRI had all of their land in SRI at any one time. Even though the adopters report higher yields from SRI than from traditional rice cultivation, even with adequate experience, farmers are unwilling or unable to put all of their land under SRI.

There is some evidence that economies of scale do exist for SRI and that using the method on a small fraction of a hectare may make it unprofitable and lead to disadoption. It is also possible that diseconomies of scale set in for larger fields, but, given that most farmers in our survey owned less than 1 ha of rice land and that farmers often own two or more fields in different locations, this question remains to be answered.

Farm and household characteristics

Who adopts is at least as important as how many farmers adopt and the extent to which they adopt if part of the impetus for promoting new technologies is poverty reduction. Yet, poorer households are typically among the last adopters of improved agricultural technologies, in part because of the positive correlation between education and both income and propensity to adopt, in part because of the effects of higher income on the financial liquidity necessary to facilitate risk-taking or, in the case of technologies requiring purchased inputs, to finance their acquisition. This empirical regularity is seen in the case of SRI as well. Table 3 presents mean household characteristics for each of the three categories of farmers.

The most striking differences are in education, farmer association membership, and land area. We did not measure income directly, but landholdings and income have previously been shown to be strongly and positively correlated among Malagasy rice farmers (Barrett and Dorosh 1996). Land tenure (not included in Table 3) is not a problem for SRI adoption at the survey sites, as nearly all farmers own most, if not

Table 3. Farmer and household characteristics (means by strata unless otherwise indicated).

Obstacle	Adopters	Disadopters	Nonadopters
Number surveyed	80	83	154
Age of household head (y)	44.6	41.7	44.4
Years of education of household head[a]	5.5	5.3	4.0
Percent belonging to a farmer association[a]	49	52	29
Number of adults in household	3.7	3.4	3.6
Number of children in household	3.3	3.0	3.3
Total lowland rice area 1999 (ha)[a]	0.67	0.66	0.54
Total lowland rice area 1993 (ha)[b]	0.56	0.61	0.46
Other crop area (ha)	0.58	0.63	0.53

[a]Nonadopter category only statistically significantly different from other categories at 5% significance level. [b]Nonadopter category only statistically significantly different from other categories at 10% significance level.

all, of the lowland area they cultivate. Consistent with much of the adoption literature, adopters and disadopters have had more years of schooling on average than nonadopters and are more likely to belong to a farmer association. More education and participation in a farmer association can both improve one's access to information on a new technique and help a farmer deal with changes required by new technologies (Feder et al 1985, Rogers 1995). So, information seems to be a factor in SRI adoption, as it is in most adoption studies. SRI adopters and disadopters also have significantly more lowland rice area on average than nonadopters, in both 1993 (before the introduction of SRI into these villages) and 1999.

The major sources of income for the household prove to be among the most important differences between those who have tried SRI and those who have not. Table 4 shows the percentage of farmers citing a given source as first or second in importance for the household. When the income sources that are widely considered signs of relative wealth—(government) salary, metal working, and milk and wheat production—are combined, 32% of adopters, 23% of disadopters, and only 8% of nonadopters tap at least one of these. Farmers who have a stable and significant nonrice source of income invest the time and money in SRI. Reliance on agricultural day labor as a major source of income is a sign of poverty in rural Madagascar, as this usually indicates that the household runs out of rice and money soon after the harvest and may be living day to day on what little it can earn. Farmers who try SRI are much less likely to depend on agricultural day labor.

In addition to the relative amount of income each source brings to the household, the timing of the income and corresponding labor requirements helps explain observed SRI adoption patterns. Potatoes, wheat, and barley are all grown in the win-

Table 4. Sources of income for households.

Source of income	Percent of farmers		
	Adopters	Disadopters	Nonadopters
Salary[a]	13	16	6
Agricultural day labor[b]	14	12	32
Nonagricultural labor	4	8	8
Traditional crafts[c]	10	25	21
Metal working	10	4	0
Commerce/trade	11	10	14
Rice[d]	25	14	15
Milk production	5	1	1
Potatoes	30	6	2
Wheat, barley	4	2	1

[a]Nonadopter category only statistically significantly different from other categories at 5% significance level. [b]Nonadopter category only statistically significantly different from other categories at 10% significance level. [c]Adopter category only statistically significantly different from other categories at 5% significance level. [d]Adopter category only statistically significantly different from other categories at 10% significance level.

ter season after the rice harvest, so their labor requirements do not conflict with those of rice and the harvest comes right before the rice-planting season, thereby helping tide the household over through at least the early parts of the rice-growing season, when SRI's additional demands are greatest (for field leveling and seedling transplanting). Small-scale milk production requires only a few hours on-farm each day and provides cash income and food year-round. Metal working is similarly flexible in its timing and in producing income across all seasons. In contrast, agricultural day labor usually involves working in other farmers' rice fields and thus directly conflicts with the household's own rice production. Although agricultural day labor provides income, most of this is used to satisfy immediate consumption needs. Salaried income requiring daily presence at an office can likewise conflict with SRI because the latter not only demands more labor than conventional rice, but it also necessitates close supervision of hired laborers, many of whom are unfamiliar with SRI methods. However, the greater importance of rice as a source of income for adopters must be treated with caution since it may be both a cause and a result of SRI adoption. With more land, adopters would be expected to grow more rice ex ante, and still more rice after adopting SRI.

These observations underscore a fundamental point often overlooked in the discussion of technology adoption: the difference between cash cost and opportunity cost. Just because an input is not purchased for cash from a market does not make it costless. All inputs have an opportunity cost, even land and labor that farmers do not always exchange through markets. For those with relatively high salary income, the opportunity cost of foregone salary seems to discourage the continued practice of SRI because this method necessitates taking more time in the fields to work and supervise hired laborers. This seems to be an important part of the SRI disadoption story. Disadopters depend more on salary and crafts income and less on other agricultural crops or milk than do adopters.

In contrast, the (minimal) opportunity cost of labor is typically the wage rate one could earn in unskilled employment. The fact that people choose to supply unskilled labor in the market signals the paucity of attractive options they face. So, it might seem that a new technology offering returns as high as SRI seems to deliver should prove especially attractive to the poor who otherwise depend on unskilled labor. However, timing matters. The returns to SRI take months to materialize, whereas agricultural wages are received daily. Since nutritional requirements must be met before the rice harvest, farmers facing a long "soudure," or hungry season, cannot afford to wait. Because the little informal credit that is available to rural Malagasy households is of very short duration—at most two or three months (Zeller 1994)—the effective interseasonal interest rate faced by the poorest Malagasy smallholders is effectively infinite. Properly discounted for the shadow value of cash, the seemingly attractive returns to SRI are probably inferior to those of unskilled agricultural labor because of the failure of rural financial systems. These all-too-common features of poor rural areas are too often overlooked by developers and analysts of new agricultural technologies for small-scale producers.

In summary, the traditional correlates of adoption—education, membership in farmer associations, and higher wealth and income—indeed seem to affect who tries SRI. Those without good information or sufficient wealth appear to face a barrier to entry to participation in the new method. The timing of one's other income and labor demands likewise matters a great deal. An activity can be thought of as complementary to SRI if it provides income that can be used to hire labor at crucial points in the rice-growing season. Off-season crops, such as barley, potatoes, and wheat, milk production, and metal working fit this description for the survey sites. Activities may conflict with SRI when their labor requirements coincide with those of SRI. Agricultural day labor and many types of salaried employment fall into this category. Income sources thereby provide important evidence that seasonal liquidity constraints affect both the initial adoption and the continued use of SRI.

The role of SRI in rural development in Madagascar

If the goal of SRI promotion is to help poor smallholder farmers in Madagascar increase rice production, this goal is largely not being met and seasonal liquidity constraints appear largely to blame. According to Minten and Zeller (2000), an estimated 60% of the farmers surveyed in four regions of Madagascar and 77% in the Ranomafana area were net buyers of rice. One can compare these figures with those on SRI adoption for all of the survey sites, where 75% of the farmers never tried SRI and 85% were not practicing it in 1999. For the Ranomafana sites, 68% never tried SRI and 87% were not practicing the method in 1999. Although these are rough correspondences only, since those who tried SRI were wealthier and had, on average, a rice stock that lasted longer before adoption, it would appear that SRI may be largely missing the net buyers among the rice-farming population and benefiting the farmers who need it less, namely, those who already produce a surplus of rice.

Net-surplus producers have consistently higher income and are endowed with more land than net buyers (Barrett and Dorosh 1996), underscoring the distributionally regressive nature of SRI as it presently stands. Poorer farmers might benefit indirectly in the long run from SRI if widespread adoption among wealthier, larger rice farmers leads to increased employment of poorer rice farmers as agricultural wage laborers and lower rice prices. However, the high rates of disadoption and low extent of adoption among those who are able to adopt, and physical water management constraints in many parts of Madagascar, suggest that these indirect effects are unlikely.

Minten and Zeller (2000) caution “against a (development) strategy that simply focuses on rice” because of the potential for increasing income inequality. This caution seems to apply to the promotion of SRI in rural Madagascar. Farmers who do not face seasonal liquidity constraints and who can hire labor are able to increase (or at least maintain) rice productivity and income, while the poorer farmers face declining productivity and continued difficulty meeting consumption needs. When rice is the primary source of income and food, the poorer farmers are faced with a classic “Catch 22”: they must grow more rice to pay for investment, but they must invest to grow more rice, even if the investment is in scarce labor rather than direct cash expenditures.

Promoting alternative sources of income, such as off-season cropping on the rice fields, that do not require labor or monetary investment during the rice-planting season or that offer flexibility in labor scheduling may help to alleviate both labor and liquidity problems. Moreover, such income sources can complement rice intensification, potentially enabling farmers to subsequently adopt SRI. Seasonal credit programs could be another way to overcome the severe seasonal liquidity constraints faced by farmers. Although results of past credit programs in Madagascar are mixed (Zeller 1994), many smallholders clearly cannot invest in rice intensification without resolving their cash flow problem.

In addition to the problems of the equitable diffusion of SRI, this study also raises questions concerning the costs of diffusion. The apparent reliance on extension and high rates of disadoption in the absence of extension suggest that it may take farmers several years to become comfortable practicing the method without assistance. Moreover, if the effect of extension is less one of learning than of conforming to authority figures' expectations, a permanent extension presence would be needed. If technical support needs to be available at the village level for extended periods, the costs of diffusing the method in Madagascar on a large scale would be quite high.

Although the experience of the communities in this study may not be entirely representative of current or potential SRI adoption in other parts of Madagascar, much less in other rice-growing regions of the world, our findings serve as a caution about the importance of seasonal liquidity and labor constraints in influencing rice-technology adoption patterns among poorer farmers. The opportunity cost of the scarce resources farmers must invest in the adoption of new technologies or assets largely determines the attractiveness of these options. Sometimes, the scarcity of cash makes labor, the only means by which the poor can earn cash, the scarcest input of all.

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Notes

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Effects of SRI practices on hybrid rice performance in Tamil Nadu, India

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This paper describes a field experiment conducted in the wetlands of Tamil Nadu Agricultural University, Coimbatore, India, to test components of the System of Rice Intensification (SRI) using hybrid rice variety CORH2.

The following four factors were studied: seedling age (14-d-old seedlings vs 23-d-old seedlings), irrigation (limited vs conventional), weeding (weeds incorporated with a conoweeder vs manual removal of weeds), and nutrient management (recommended amount of fertilizer with and without green manure). The experiment was a strip-plot design in four replicates.

The results show savings in irrigation water of 56% and 50% using conventional and young seedlings, respectively, without a significant effect on grain yield. The average grain yield for the limited irrigation treatment (6,352 kg ha^{-1}) was not significantly different from that of the conventional irrigation practice (6,461 kg ha^{-1}). No significant main effect of seedling age and nutrient management was found. In situ incorporation of weeds increased yield significantly to 6,737 kg ha^{-1} compared with that of conventional weeding of 6,076 kg ha^{-1}. A significant interaction was found among weeding, seedling age, and nutrient management. The highest yields for both conventional and limited irrigation conditions were obtained with a combination of young seedlings, green manure application, and incorporation of weeds using a conoweeder. This implies that our attempts to reduce water use in rice cultivation will have to be accompanied with a set of appropriate agronomic measures.

The state of Tamil Nadu, India, has about 2 million ha of rice area. Irrigated rice cultivation using transplanted seedlings is common in Tamil Nadu. Irrigation to 5-cm depth 1 day after the disappearance of floodwater is the recommended water management. The total available irrigated area in Tamil Nadu is 1.08 ha per capita vis-à-vis 1.7 ha per capita for all of India. In Tamil Nadu, 70% of the irrigated area is under rice. It is estimated that the water supply-demand gap for irrigated crops will be about 21 10^9 m^3 in 2025 (Palanisamy and Paramasivam 2000). It is also estimated that the domestic and industrial use of water, which currently claims 15% of the water resources, is expected to increase to 25% in 2025. Under these circumstances, water savings in irrigated rice production is of paramount importance to meet future water demand.

Therefore, water-saving irrigation techniques are receiving renewed attention (Bouman and Tuong 2001). Alternate wetting-and-drying practices resulted in both water savings and yield losses of 0–70% compared with flooded treatments, depending on the number of days between irrigations and existing soil conditions (Bouman and Tuong 2001). Alternate wetting and drying has been promoted in China since 1990 (Li 2001).

The System of Rice Intensification (SRI) developed in Madagascar has been reported to increase the grain yield of rice substantially (Uphoff 2001). This system is composed of a package of agronomic measures that should be applied simultaneously to realize a yield increase. The components of SRI include the use of young seedlings, a single seedling per hill, wide spacing of transplanted seedlings, limited irrigation, aerated soil conditions by frequent disturbance of the soil, and the use of compost. Since water savings and a yield increase are important objectives in Tamil Nadu, components of the SRI management package were tested.

Objective

The overall objective of the experiment was to compare SRI cultivation practices with conventional practices for the growth and yield of rice. Special emphasis was on determining the effects of limited irrigation, the use of young seedlings, mechanical weeding and incorporation of weeds, and green manure application.

Materials and methods

An experiment was conducted with the rice hybrid CORH2 (125 d duration) from September 2001 to January 2002 on the wetland farm of Tamil Nadu Agricultural Univerisity, Coimbatore (11°N, 77°E). The clay loam soil at the experimental site had a pH of 8.3, its electrical conductivity was 0.54 dS m^{-1}, organic carbon content was 8.2 g kg^{-1}, available N ($KMnO_4$-N) was 232 kg ha^{-1}, Olsen-P was 32 kg ha^{-1}, and available K (NH_4OAc-K) was 740 kg ha^{-1}.

The experiment consisted of four factors, each with two levels. The treatment combinations were replicated four times in a strip-plot design. The four factors and their levels are

Seedling age P1: conventional seedlings, 23-d-old seedlings, a single seedling $hill^{-1}$.

	P2: young seedlings, 14-d-old seedlings raised in a dapog nursery[1], a single seedling $hill^{-1}$.
Irrigation	I1: conventional irrigation to 5-cm depth 1 day after the disappearance of ponded water.
	I2: limited irrigation to 2-cm depth after surface crack development. This practice was pursued up to flowering. Thereafter, I1 was practiced.
Weeding	W1: hand weeding and removal of weeds from the field (total, 3 weedings).
	W2: incorporating weeds with conoweeder (total, 5 weedings).
Nutrient	N1: recommended N (150 kg ha^{-1}), P_2O_5 (60 kg ha^{-1}), K_2O (60 kg ha^{-1}), and $ZnSO_4$ (25 kg ha^{-1}).
	N2: recommended N, P, K, and Zn + fresh daincha green manure (6.25 t ha^{-1}).

A plant density of 25 m^{-2} (square planting, 20 × 20 cm) was used for all treatments vis-à-vis the common conventional plant density of 50 m^{-2} (20 × 10 cm) to facilitate the criss-cross use of the conoweeder.

Tiller density at different growth stages of the crop was computed according to the procedure described by Thiyagarajan et al (1995). Root volume was measured using a volume displacement technique. Harvest index and biomass were determined using a sampling strategy similar to that used for tiller density. Grain yield was recorded at the harvest of each plot and expressed at 14% moisture content. Irrigation water input was estimated using V-notches.

Results

Grain yield

The grain yield of all treatments ranged from 5,059 to 7,612 kg ha^{-1} (Table 1). There were no significant differences in grain yield for the two types of seedlings (P), the two irrigation levels (I), and the two nutrient management treatments (N). However, the two weeding treatments (W) showed significant differences in yield. In addition, significant interaction effects were found for weeding with age of seedlings (W × P) and with nutrient management (W × N), and for age of seedlings, weeding, and nutrient management (P × W × N).

Incorporation of weeds and disturbance of the soil with a conoweeder significantly increased grain yield to 6,737 kg ha^{-1} vis-à-vis conventional weeding practices, which yielded 6,076 kg ha^{-1}. Irrigation and nutrient levels did not have a sig-

[1]Dapog nursery is a method of raising seedlings on a polythene sheet with a thin layer of a medium consisting of soil, sand, and manure to grow young seedlings.

Table 1. Grain yield (kg ha^{-1}) in a field experiment with four different agronomic measures (seedling age, irrigation, weeding, and nutrient management), September 2001 to January 2002, Coimbatore, India.

Item		Conventional seedlings (P1)		Young seedlings (P2)			
		Conventional irrigation (I1)	Limited irrigation (I2)	Conventional irrigation (I1)	Limited irrigation (I2)	Mean	Mean
Conventional weeding (W1)	Recommended nutrients (N1)	6,151	6,199	6,841	6,268	6,365	6,076
	N1 + green manure (N2)	6,000	6,195	5,893	5,059	5,787	
Weeds incorporated (W2)	Recommended nutrients (N1)	6,008	6,908	6,838	6,707	6,615	6,737
	N1 + green manure (N2)	6,343	6,349	7,612	7,126	7,369	
Mean		6,126	6,413	6,796	6,290		
Mean		6,269		6,543			

Main factors	LSD (0.05)	Interactions	LSD (0.05)	Interactions	LSD (0.05)
Seedling age (P)	ns[a]	P × I	ns	I × N	ns
Irrigation (I)	ns	P × W	932	P × I × W	ns
Weeding (W)	361	P × N	ns	P × I × N	ns
Nutrients (N)	ns	I × W	ns	P × W × N	959

[a]ns = not significant.

nificant effect with conventional seedlings (P1) and weeding (W1). However, conventional seedlings with weed incorporation (W2) and the recommended amount of nutrients (N1) resulted in significantly higher yield (15%) under limited irrigation (I2) than under conventional irrigation (I1). Similarly, combining conventional seedlings (P1), limited irrigation (I1), and the recommended level of nutrients (N1) with the incorporation of weeds (W2) significantly increased yield (11%) compared with conventional weeding (W1).

Green manure application (N2) significantly reduced yield under both conventional (–14%) and limited irrigation (–19%) when combined with young seedlings (P2) and conventional weeding (W1). However, when weeds were incorporated (W2) under the same conditions, there was a positive effect on grain yield: an increase of 29% with conventional irrigation and 41% with limited irrigation when compared with conventional weeding.

Green manure application (N2) and conventional weeding (W1) did not have a significant effect on grain yield with conventional irrigation (I1) and both types of seedlings (P1 + P2). However, under limited irrigation (I2), grain yield declined significantly (18%) using young seedlings (P2) compared with using conventional seedlings (P1). Green manure application (N2) in combination with weed incorporation (W2) significantly increased the yield with young seedlings compared with conventional seedlings under both conventional (+20%) and limited irrigation (+16%) regimes, but the effect was significant only under conventional irrigation (7,612 kg ha^{-1}).

For both methods of irrigation, the highest yields were obtained for the combination of young seedlings (P2), green manure application (N2), and weed incorporation (W2).

Water use

Using conventional seedlings, the amount of irrigation water used was 11,853 and 5,205 m^3 ha^{-1} for the conventional and limited irrigation treatments, respectively. This implies a savings of irrigation water of 56% (Table 2) without any significant effect on grain yield. The growth period of the crop raised using young seedlings was 13 d longer than that of the conventionally raised crop. Consequently, it received two additional irrigations during the grain-filling period and the total amount of irrigation water was 13,347 and 6,699 m^3 ha^{-1} in the conventional and limited irrigation treatments, respectively. Here, savings in irrigation water was 50%. The water productivity, defined as the grain yield divided by the total amount of water supplied (rainfall + irrigation), was on average 0.40 and 0.67 kg m^{-3} for the conventional and limited irrigation, respectively.

Tiller density

At the active tillering stage (21 days after transplanting, DAT), limited irrigation resulted in a significantly higher tiller density than conventional irrigation. Other factors did not show any significant effect. Limited irrigation resulted in higher tiller density throughout the rest of the growth period (Fig. 1).

Table 2. Characteristics of water input and use in a field experiment with conventional and young seedlings under conventional and limited irrigation, September 2001 to January 2002, Coimbatore, India.

Item	Conventional seedlings		Young seedlings	
	Conventional irrigation	Limited irrigation	Conventional irrigation	Limited irrigation
Total irrigation water (m^3 ha^{-1})	11,853	5,205	13,347	6,699
Total number of irrigations	14	9	16	11
Cumulative rainfall during the crop period (m^3 ha^{-1})	3,560	3,560	3,560	3,560
Total water used (m^3 ha^{-1})	15,413	8,765	16,907	10,259
Water productivity (kg m^{-3})	0.398	0.732	0.402	0.613

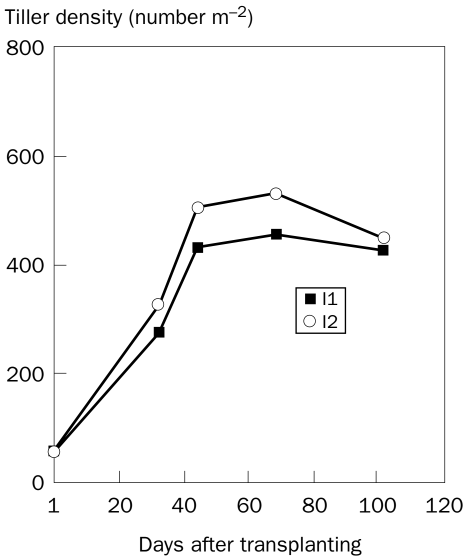

Fig. 1. Effect of irrigation methods on tiller density. I1 = conventional irrigation, I2 = limited irrigation.

At the panicle initiation stage, there were significant differences in the number of tillers for seedling age, irrigation, and weeding and a significant interaction for seedling age with irrigation. Under conventional irrigation, young seedlings had 33% more tillers than conventional seedlings. Under limited irrigation, this difference was only 11%. The conoweeder operations resulted in a significantly higher tiller density (534 tillers m^{-2}) compared with manual weeding (503 tillers m^{-2}).

The significant differences in the number of tillers because of seedling age and the interaction effect for seedling age and irrigation remained till the flowering stage.

Root volume

Root volume increased from planting to the flowering stage and declined at the grain-filling stage (Fig. 2). At the active tillering stage, the root volumes of conventional and young seedlings were almost comparable. The increase in root volume from active tillering to panicle initiation was 110% in the young seedlings and 73% in the conventional seedlings. Limited irrigation, weeding using a conoweeder, and the application of green manure significantly increased root volume only at the panicle initiation stage. The use of a conoweeder, resulting in disturbance of the soil surface, increased root volume under both nutrient management practices. The effect, however, was more pronounced in the green manure treatment.

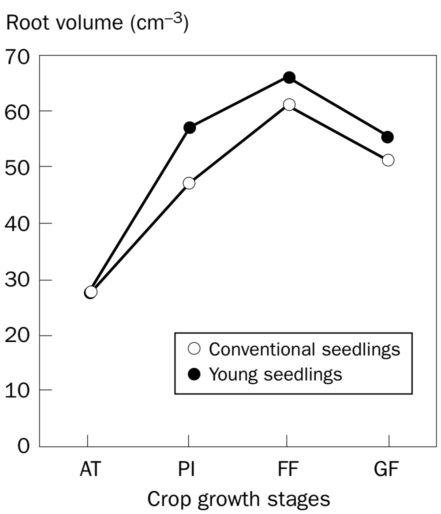

Fig. 2. Effect of the age of seedlings on root volume at active tillering (AT), panicle initiation (PI), 50% flowering (FF), and grain filling (GF).

Conclusions and discussion

The study showed a savings in irrigation water of 56% to 50% for conventional and young seedlings, respectively, without a significant effect on grain yield of rice.

The period of experimentation coincided with the northeast monsoon, with considerable rainfall, which reduced the amount of water needed for irrigation. Water productivity was highest for limited irrigation with conventional seedlings. Using young seedlings, water productivity decreased 16% because of the longer growth period and, consequently, larger number of irrigations. This study shows that limited irrigation can increase water productivity (grain yield per total water input) by 84% with conventional seedlings and by 52% with young seedlings.

There was no significant difference between the mean yield of conventional seedlings (23 d old) and young seedlings (14 d old), suggesting that the use of young seedlings does not have a yield advantage, contrary to what has been observed by Uphoff (2001).

Though green manure application under conventional weeding had a significant negative effect on yield, the positive interactions of green manure application combined with weed incorporation showed that a combination of agronomic measures may result in high yields. At the same experimental site, Janaki et al (2000) found no significant yield effect for the application of green manure.

Our study shows that weed incorporation has a positive yield effect, perhaps because of soil aeration caused by the use of the conoweeder. This could have resulted in a favorable root environment, responsible for the higher tiller density and root volume observed in this study.

The use of young seedlings and weed incorporation showed the highest yields of 7.6 and 7.1 t ha^{-1} for conventional and limited irrigation, respectively. Conventional seedlings with conventional weeding resulted in only 6.0 and 6.2 t ha^{-1} for conventional and limited irrigation, respectively. These results show that there is a yield increase of 1.6 t ha^{-1} for conventional irrigation and 0.9 t ha^{-1} for limited irrigation because of seedling age and weeding practices.

The significant increase in grain yield and root volume because of the incorporation of weeds is a new finding in the study, which has to be verified using standardized methods. The favorable effect of young seedlings on root volume and tiller density is also an important aspect that needs to be explored.

The significant yield increase because of weed incorporation with the conoweeder and the significant interaction effect for the age of seedlings and weed and nutrient management reveal the possibility for creating synergy among agronomic practices. This implies that an entire package of agronomic practices will have to be considered in our attempt to transform inundated rice cultivation practices into practices that use much less water.

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System of Rice Intensification (SRI): evaluation of seedling age and selected components in Indonesia

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The five major components of the System of Rice Intensification (SRI) are (1) the use of young seedlings at the 2-leaf stage (8–15 days) with one seedling per hill, (2) wide spacing (0.25 × 0.25 m to 0.5 × 0.5 m), (3) a minimum of three weedings at 10–12, 22–25, and 40–42 days after transplanting, (4) intermittent drainage and drying for soil aeration during the vegetative stage, and (5) the addition of organic matter (manure and/or compost) to supply adequate nutrients. As a package, SRI is reported to produce substantial (50% to 200%) increases in grain yield through the mutual interaction of all these components. However, information and data are scarce on the relative contribution of individual components to yield formation. This paper provides on-farm experimental data and information from Indonesia on the interaction between seedling age and number of seedlings per hill, plant spacing, rates and types of organic matter addition, and intermittent irrigation. In each on-farm trial, two to three components were tested, keeping all other components constant. Continuous irrigation was used in all trials except the one in South Sulawesi that evaluated continuous and intermittent irrigation. Farmer cooperators and local researchers jointly managed these trials and evaluated the results. At 1 seedling $hill^{-1}$, 15-d-old seedlings produced significantly higher yield (6.43 t ha^{-1}) than the farmers' practice of using 21-d-old seedlings (5.96 t ha^{-1}) in Pasar Miring village of North Sumatra. However, yields were similar for both age groups when the number of seedlings increased to 2 and 4 $hill^{-1}$. In Mattoangin village, South Sulawesi, dibbling pregerminated seed at 1 seed $hill^{-1}$ produced a grain yield of 6.19 t ha^{-1} vis-à-vis 7.11 t ha^{-1} for 15-d-old seedlings and 6.13 t ha^{-1} for 21-d-old seedlings in the transplanting system with a single seedling per hill. This indicates that direct wet seeding with 1 seed $hole^{-1}$ cannot replace transplanting with <15-d-old seedlings at 1 seedling $hill^{-1}$. The performance of 15-d-old seedlings improved more than that of 21-d-old seedlings with the addition of well-decomposed organic matter at 2 t ha^{-1} and with intermittent irrigation; however, the addition of poorly decomposed organic matter adversely affects young seedlings more than older ones. Indonesian farmer-cooperators' reactions to the transplanting of young seedlings at 1 $hill^{-1}$ and their effect on the adoption of this practice are discussed.

New high-yielding, short-duration rice varieties are being bred and used increasingly in intensive rice systems to meet the growing food demand in many Asian countries (Hossain 1999). Generally, rice varieties are sensitive to the age of seedlings at the time of transplanting. After transplanting, younger seedlings, especially of short-duration varieties, recover faster than older ones and grow vigorously to produce high yield. Wiengweera (1984) reported that the grain yields of young seedlings of IR58 and IR36 (short duration, 100–110 d) were higher than those of the old seedlings because of higher panicle and spikelet numbers per unit area and higher percent filled grain and 1,000-grain weight. In this study, the yield of IR58 increased when the number of seedlings hill^{-1} increased from 3 to 6. Cada and Taleon (1963) suggested 25–30-d-old seedlings as optimum for early maturing varieties. Patel et al (1978) observed that yield was the highest for 21-d-old seedlings vis-à-vis a yield reduction of 16% and 32% for 28- and 35-d-old seedlings, respectively. According to Herrera and Zandstra (1980), old seedlings mature later because of the delayed formation of tillers and longer time to recover from transplanting shock. Enyi (1962) showed that young seedlings had a greater rate of leaf production and earlier panicle initiation than old seedlings. The tillering capacity of rice decreases if plants remain long in the seedbed (Singh and Bhattacharya 1974). Thus, seedling age and numbers hill^{-1} play an important role in crop growth and yield of short-duration varieties.

In the System of Rice Intensification (SRI), the use of young seedlings is combined with several other components to boost rice yields (Uphoff 2002). The five major components of the SRI are (1) the use of young seedlings at the 2-leaf stage (8–15 days) with 1 seedling hill^{-1}, (2) wide spacing (0.25×0.25 m to 0.5×0.5 m), (3) a minimum of three weedings at 10–12, 22–25, and 40–42 days after transplanting, (4) the addition of organic matter (manure and/or compost) to supply adequate nutrients, and (5) intermittent drainage and drying for soil aeration during the vegetative stage. The most difficult component of the SRI to evaluate is the intermittent irrigation, which requires coordinated changes at the community and/or basin level. As a package, the SRI is reported to produce substantial increases (50–200%) in grain yield through the mutual interaction of all these components (Uphoff 2002). However, information and data are scare on the relative contribution of individual components to yield formation. The objective of this study conducted in Indonesia under the Integrated Crop Management (ICM) project was to examine the interaction between seedling age and number of seedlings hill^{-1}, plant spacing, rates and types of organic matter addition, and intermittent irrigation.

Materials and methods

Seven on-farm experiments on seedling age versus number per hill, spacing, organic matter addition, and water management were conducted in six villages representing six provinces of Indonesia: (1) Pasarmiring research station, North Sumatra, (2) Pasar Pakandangan, West Sumatra, (3) Sukasenang, West Java, (4) Tembalang, East Java, (5) Tunjuk, Bali, and (6) Mattoangin, South Sulawesi. Tables 1 and 2 present site characteristics and treatment details, respectively. Farmer-cooperators of the ICM

Table 1. Characteristics of the experimental sites, Indonesia (2000-01).

Village	Characteristics		
	Climate[a]	Soil characteristics	Cropping system
1. Pasar Miring, North Sumatra	E2-type climate; 3 wet months and 5 dry months	Inceptisol (alluvial); sandy clay; high iron content	Rice-rice-secondary crops
2. Pasar Pakandangan, West Sumatra	High rainfall; 12 wet months (>200 mm month^{-1})	Inceptisol; silty loam to sandy loam texture	Five rice crops per 2 years (rice-fallow-rice-fallow-rice)
3. Sukasenang, West Java	D-type climate; 6 wet months and 4 dry months	Andosols; black, fertile soil, deep plow layer (>0.2 m), high organic matter content	Rice-rice-rice or rice-rice-vegetables/ upland crops
4. Tembalang, East Java	Rainy season: Nov-Apr; dry season: Apr-Dec	Inceptisol; silty clay texture; pH neutral to slightly alkaline	Rice-rice-fallow
5. Tunjuk, Bali	E-type climate; Oct-Feb is rainy season; Jul-Oct is dry season	Oxisol; sandy clay loam to sandy loam texture; pH 6.5 ± 0.5	Rice-upland crops-rice; 10% vegetables and flowers in all season
6. Mattoangin, South Sulawesi	OC-type climate; Oct-Apr is rainy season; Jun-Sep is dry season. Annual rainfall 3,746 mm	Inceptisol; clayey texture	Rice-rice-upland crops (mungbean and/or vegetables)

[a]Climate type classification is according to Oldeman (1975), Oldeman and Sjarifuddin (1977), Oldeman et al (1979, 1980).

project and local researchers jointly managed these trials. While researchers carefully collected and analyzed the data of all trials, farmers evaluated the same trials using their own criteria for the adoption of new techniques or practices.

All crop management practices except the SRI components were according to local recommendations or farmers' practices. Land was prepared wet using a hand tractor (1–2 plowings/harrowings). Seed rate ranged from 25 to 40 kg ha^{-1} for treatments with plantings of 3 to 6 seedlings hill^{-1} and 10 to 15 kg ha^{-1} for the SRI method of planting 1 seedling hill^{-1}, with certified seed. Unless mentioned, 3 to 6 seedlings were transplanted hill^{-1}. Continuous irrigation was used in all trials except the one in South Sulawesi. Weeds were controlled manually three times per crop. Pest control was done based on need. The crop was harvested manually using a sickle and then threshed by a thresher.

Phosphorus (P) and potassium (K) were applied based on soil test results. Sulfur and zinc were applied at deficient sites based on local recommendations. Unless mentioned, nitrogen (N) application was based on the leaf color chart (LCC). The

Table 2. Treatments of the seedling experiments conducted in six villages of Indonesia, 2001 dry season.

Location	Seedling age (d)	Number of seedlings hill^{-1}	Other treatments[a]	Number of treatments
1. Pasar Miring, North Sumatra	15 and 21	1, 2, and 4	–	6
2. Pasar Pakandangan, West Sumatra	10, 15, and 20	1, 3 and 5	–	9
3. Sukasenang, West Java	15 and 21 15 and 21	1 for 15-d-old seedlings and 3–6 for 21-d-old seedlings	Plant spacing (25 ×25 cm, *legowo*); straw compost (0 and 2 t ha^{-1})	8
4a. Tembalang, East Java	15 and 21	–	Plant spacing (0.15 × 0.15 m; 0.2 × 0.2 m; 0.25 × 0.25 m, and *legowo*)	8
4b. Tembalang, East Java	15 and 21	–	Organic matter (FYM, rice straw, no OM); K application (0 and 50 kg KCl ha^{-1}); NPK	14
5. Tunjuk, Bali	15 and 21	–	N fertilizer (N-recommendation vs LCC), organic matter (2 t FYM ha^{-1} vs no FYM)	8
6. Mattoangin, South Sulawesi	0 (wet seeding), 15, and 21	1 and 3 1 and 3	Water management (continuous vs intermittent flooding)	12

[a]FYM = farmyard manure, OM = organic matter, LCC = leaf color chart.

LCC consists of six color shades ranging from light yellowish green (No. 1) to dark green (No. 6). An LCC critical value of 4 was used to determine the time of N application and the amount per application, that is, 23 kg N ha^{-1} (IRRI-CREMNET 2000). Farmers measured the leaf color every 10 days from 14 days after transplanting to first flowering. They randomly selected at least 10 disease-free plants in an area with a uniform plant population. The color of the youngest fully expanded leaf was compared with the color strips of the chart and the number of leaves that read below the set critical value was determined. If more than five leaves read below the critical value, farmers topdressed N as prilled urea.

Results and discussion

North Sumatra

At 1 seedling hill^{-1}, 15-d-old seedlings yielded significantly higher than 21-d-old seedlings. With 2 and 4 seedlings hill^{-1}, the difference because of seedling age was not evident (Table 3). The main factors of seedling age in relation to seedling number

Table 3. The effects of seedling age and number of seedlings hill^{-1} on grain yield (14% moisture content, t ha^{-1}) of IR42 at Pasar Miring, North Sumatra, 2001 direct seeding.[a]

No. of seedlings hill^{-1} (SN)	Seedling age (d) (SA)		Mean of SN
	15	21	
1	6.43 a	5.96 c	6.20 A
2	6.14 bc	6.22 ab	6.18 A
4	6.22 ab	6.18 bc	6.20 A
Mean of SA	6.26 A	6.12 A	

LSD (0.05): SA = ns; SN = ns, SA × SN = 0.22

[a]In Tables 3 to 9, the mean values in each column or row followed by the same letters (lowercase for interaction factors and uppercase for main factors) are not significantly different by Duncan's multiple range test. * = significant at $P = 0.05$, ns = not significant at $P = 0.05$.

hill^{-1} or seedling number hill^{-1} in relation to both seedling ages did not significantly influence yield. Thus, old seedlings appear to yield as high as young seedlings if the number of seedlings hill^{-1} is increased.

West Sumatra

At this site, seedlings at three ages (10, 15, and 20 days) were tested at 1, 3, and 5 seedlings hill^{-1}. The mean yields of the main factors were not significantly different, but the interaction between seedling age and number hill^{-1} was significant. The highest grain yield was obtained at 1 seedling hill^{-1} for 10-d-old seedlings, 3 hill^{-1} for 15-d-old seedlings, and 5 hill^{-1} for 20-d-old seedlings (Table 4). Grain yield for 20-d-old seedlings at 5 hill^{-1} was lower than that of 15-d-old seedlings at 3 hill^{-1}. This shows that, to a limited extent, grain yields can be maintained by adjusting the number of seedlings hill^{-1} for seedlings of different age groups.

West Java

In this trial, the main effect of seedling age and the effect of seedling age in relation to planting pattern were not significant, but the interaction effects were significant (Table 5). Planting of 15-d-old seedlings at 1 seedling hill^{-1} in a 0.25 × 0.25 m square pattern gave a higher yield (5.1 t ha^{-1}) than planting in the *legowo* system, that is, paired rows with a spacing of 0.125 m between rows in a pair and 0.5 m between pairs (4.4 t ha^{-1}) when no organic matter was added to the soil. With the addition of 2 t ha^{-1} of rice straw compost, yield declined to 3.7 to 3.9 t ha^{-1} and no difference was observed between planting patterns. For 21-d-old seedlings, both patterns gave similar yields (4.7 to 4.8 t ha^{-1}) with no addition of organic matter, while the square pattern yielded higher than the *legowo* system with the addition of 2 t ha^{-1} of organic matter. The addition of straw compost decreased the yield of 15-d-old seedlings at 1 hill^{-1} (from 4.75 to 3.80 t ha^{-1}) more than that of 21-d-old seedlings at 3–6 hill^{-1} (from 4.75 to

Table 4. The effects of seedling age and number of seedlings hill^{-1} on grain yield (14% moisture content, t ha^{-1}) of rice variety IR42 in Pakandangan village, West Sumatra, 2001 direct seeding.

Number of seedlings hill^{-1} (SN)	Seedling age (d) (SA)			Mean of SN
	10	15	20	
1	5.65 ab	5.13 b	5.25 b	5.34 A
3	4.69 b	5.71 a	5.04 b	5.15 A
5	4.75 b	5.39 b	5.44 b	5.19 A
Mean of SA	5.03 A	5.41 A	5.24 A	

LSD (0.05): SA = ns, SN = ns; SA × SN = 0.51*

Table 5. The effects of seedling age on grain yield (14% moisture content, t ha^{-1}) of rice variety Widas as influenced by the addition of straw compost and planting system at Sukasenang village, Garut, West Java, 2001 direct seeding.

Treatments[a]	Seedling age (d) (SA)		Mean
	15	21	
OM-0, CS-25	5.10 a	4.80 ab	4.95 a (OM-0 × CS-25)
OM-0, CS-L	4.40 ab	4.70 ab	4.55 ab (OM-0 × CS-L)
OM-2, CS-25	3.70 b	5.10 a	4.40 bc (OM-2 × CS-25)
OM-2, CS-L	3.90 b	4.10 b	4.00 c (OM-2 × CS-L)
Mean SA at OM-0	4.75 a	4.75 a	4.75 A (OM-0)
Mean SA at OM-2	3.80 b	4.60 a	4.20 B (OM-2)
Mean SA at CS-25	4.40 ab	4.95 a	4.68 A (CS-25)
Mean SA at CS-L	4.15 b	4.40 ab	4.28 A (CS-L)
Mean SA	4.28 A	4.68 A	–

LSD (0.05): SA or CS = ns, OM = 0.50*, SA × OM = 0.55*, SA × CS = 0.55*, OM × CS = 0.50*, SA × OM × CS = 0.71*

[a]OM-0 = without organic matter (straw compost), OM-2 = with 2 t ha^{-1} straw compost; CS-25 = equal spacing 0.25 × 0.25 m, CS-L = *legowo* (0.25 × 0.125) × 0.5 m; seedling number was 1 hill^{-1} for 15-d-old seedlings and 3–6 hill^{-1} for 21-d-old seedlings.

4.60 t ha^{-1}). This decrease in yield was not caused by a lower number of tillers in plots treated with rice straw compost; productive tillers hill^{-1} were 20 and 18 for 15-d-old seedlings and 18 and 17 for 21-d-old seedlings in plots treated with and without compost, respectively. The straw compost used in this trial was not fully decomposed and was added just before transplanting. In such a situation, the straw compost could have immobilized available N and/or released organic acids in the root zone and thus adversely affected the recovery and early growth of 15-d-old seedlings more than those of 21-d-old seedlings. The straw should be well decomposed and applied at least 2 wk before transplanting to avoid such adverse effects on seedling growth and recovery after transplanting.

East Java

In the first trial, the two main factors (seedling age and plant spacing) and their interaction produced significant differences in grain yield (Table 6). Maximum yields were obtained for both 15- and 21-d-old seedlings at 0.25 × 0.25 m square planting. In the SRI, wider spacing and square planting facilitate the stirring of the soil by a mechanical weeder in both directions; this is said to promote vigorous growth and tillering, which could result in high grain yield from young seedlings (Uphoff 2002).

In the second trial, the effect of seedling age and organic matter addition as rice straw or farmyard manure with or without K fertilizer was evaluated (Table 7). Young (15-d-old) seedlings planted at 1 hill^{-1} produced significantly higher grain yield (7.17 t ha^{-1}) than 21-d-old seedlings planted at 3–4 hill^{-1} (6.66 t ha^{-1}). There was no significant difference in mean yields of 0 or 2 t ha^{-1} organic matter treatments with farmyard manure or rice straw. The addition of K fertilizer along with organic matter generally increased the yield over that of organic matter alone, but the difference was significant only for 21-d-old seedlings under rice straw application (Table 7). This site seems to respond well to K application and the benefits were more evident with 21-d-old seedlings.

Bali

This trial compared three factors: seedling age, organic matter level, and type of N management. Grain yield differences were significant only for certain interactions but not for any of the main factors (Table 8). With the addition of 2 t ha^{-1} of organic matter and the application of N by local recommendations, 15-d-old seedlings produced significantly higher yield (7.03 t ha^{-1}) than 21-d-old seedlings (5.94 t ha^{-1}); but, with real-time N management using the LCC, the yield difference between the two age groups was not significant. Thus, the LCC-based N management seems to be important for fertilizing the crop at the right time, irrespective of the age of the seedlings.

Table 6. The effects of seedling age and plant spacing on grain yield (14% moisture content, t ha^{-1}) of rice variety Singkil at two levels of organic matter and potassium application in Tembalang village, Blitar, East Java, 2001 direct seeding.

Plant spacing (PS)	Seedling age (d) (SA)		Mean
	15	21	
0.15 × 0.15 m	6.46 bc	6.09 c	6.28 B
0.2 × 0.2 m	7.25 ab	6.88 abc	7.07 AB
0.25 × 0.25 m	7.72 a	7.09 abc	7.41 A
Jajar legowo	7.10 abc	6.35 c	6.73 AB
Mean for SA	7.13 A	6.60 B	

LSD (0.05): SA = 0.51*, PS = 0.74*, SA × PS = 1.05*

Table 7. The effects of seedling age on grain yield (14% moisture content, t ha^{-1}) of rice variety Singkil at two levels and types of organic matter and potassium application in Tembalang village, Blitar, East Java, Indonesia, 2001 direct seeding.

Fertilizer and organic matter[a]	Seedling age (d) (SA)		Mean
	15	21	
OM-0	6.84 abcd	6.26 cd	6.55 a
OM-0 + K	7.02 abcd	7.14 abc	7.08 a
OM-2-FYM	7.18 abc	6.47 bcd	6.83 a
OM-2-FYM + K	7.59 a	6.53 bcd	7.06 a
OM-2-RS	6.90 abcd	6.11 d	6.51 a
OM-2-RS + K	7.33 ab	7.09 abc	7.21 a
Mean SA × OM-0	6.93 ab	6.70 ab	6.82 A (OM0)
Mean SA × OM-2-FYM	7.39 a	6.50 b	6.95 A (OM2-FYM)
Mean SA × OM-2-RS	7.12 ab	6.60 b	6.86 A (OM2-RS)
NPK recommendation	7.33 a	7.02 ab	7.18 A (NPK recommendation)
Mean	7.17 A	6.66 B	

LSD (0.05): SA = 0.50*, OM = ns, SA × OM = 0.74*, SA × OM × K = 0.91*

[a]OM-0 = without organic matter, OM-2-FYM = farmyard manure at 2 t ha^{-1}; OM-2-RS = rice straw compost at 2 t ha^{-1}; + K = 50 kg KCl ha^{-1} applied once, NPK rec. = based on local recommendation, namely, 300 kg urea + 75 kg SP-36 + 50 kg KCl ha^{-1}.

Table 8. The effects of seedling age, N fertilizer application, and organic matter addition on rice grain yield (14% moisture content, t ha^{-1}) at Tunjuk village, Tabanan, Bali, Indonesia, 2001 direct seeding.

Treatments[a]	Seedling age (d) (SA)		Mean
	15	21	
N-rec., OM-0	6.89 ab	6.40 bc	6.64 a (N-rec. × OM-0)
N-LCC, OM-0	7.09 a	6.94 ab	7.02 a (N-LCC × OM-0)
N-rec., OM-2	7.03 ab	5.94 c	6.48 a (N-rec. × OM-2)
N-LCC, OM-2	6.93 ab	6.78 ab	6.86 a (N-LCC × OM-2)
Mean SA × OM-0	6.99 a	6.67 ab	6.83 A (OM-0)
Mean SA × OM-2	6.98 a	6.36 b	6.67 A (OM-2)
Mean SA × N-rec.	6.96 a	6.17 b	6.57 A (N-rec.)
Mean SA × N-LCC	7.01 a	6.86 a	6.94 A (N-LCC)
Mean SA	6.99 A	6.51 A	

LSD (0.05): SA/OM/N = ns, SA × N = 0.65*, SA × OM= 0.57*, N × OM = ns, SA × N × OM = 0.64*

[a]N-rec. = N-standard application (300 kg urea ha^{-1} in 2–3 splits), N-LCC = N application based on LCC reading, OM0 = without OM, OM-2 = 2 t OM ha^{-1}.

South Sulawesi

At this site, seedling age including direct wet seeding, number of seeds or seedlings $hill^{-1}$, and type of irrigation were evaluated. The main effect of irrigation is not significant. However, the three-way interaction among seedling age, number $hill^{-1}$, and type of irrigation is significant. Under both types of irrigation, 15-d-old seedlings planted at 1 $hill^{-1}$ yielded significantly higher (7.11 and 6.75 t ha^{-1}, respectively, for intermittent and continuous irrigation) than either 21-d-old seedlings (6.13 and 5.98 t ha^{-1}) or direct wet-seeded rice (6.19 and 6.06 t ha^{-1}) (Table 9). With 3 seedlings $hill^{-1}$, 15- and 21-d-old seedlings produced similar yields under both types of irrigation. Dibbling pregerminated seeds at 1 and 3 seeds $hole^{-1}$ could not produce yields as high as that of 15-d-old seedlings under both types of irrigation.

Table 9. The effects of seedling age on grain yield (14% moisture content, t ha^{-1}) of rice variety Ciliwung at different water management and seedling number $hill^{-1}$ in Mattoangin village, South Sulawesi, Indonesia, 2001 direct seeding.

Treatments[a]	Seedling age (SA) (d)			
	0#	15	21	Mean
WMi, SN1	6.19 b	7.11 a	6.13 bc	6.43 a
WMi, SN3	5.87 c	6.46 b	6.11 bc	6.15 a
WMf, SN1	6.06 b	6.75 a	5.98 b	6.26 a
WMf, SN3	6.05 b	6.51 a	6.55 a	6.37 a
Mean SA × WMi	6.03 b	6.79 a	6.12 b	6.31 A (WMi)
Mean SA × WMf	6.06 b	6.63 a	6.27 b	6.32 A (WMf)
Mean SA × SN1	6.13 b	6.93 a	6.06 b	6.37 A (SN1)
Mean SA × SN3	5.96 b	6.49 a	6.33 ab	6.26 A (SN3)
Mean SA	6.04 B	6.71 A	6.19 B	

LSD (0.05): SA = 0.48*, WM/SN = ns, SA × WM = 0.34*, SA × SN = 0.69*, SN × WM = ns, SA × SN × WM = 0.65*

[a]WMi = intermittent irrigation, WMf = continuous flooding, SA-0# direct wet seeding = pregerminated seeds were dibbled at 1 and 3 seeds $hole^{-1}$ in puddled soil, SN1 = 1 seedling $hill^{-1}$ SN3 = 3 seedlings $hill^{-1}$.

General discussion and summary

Generally, 15-d-old seedlings gave significantly higher grain yields than 21-d-old seedlings when a single seedling was planted hill^{-1}. In West Sumatra, the highest grain yield was obtained at 1 seedling hill^{-1} for 10-d-old seedlings, 3 hill^{-1} for 15-d-old seedlings, and 5 hill^{-1} for 20-d-old seedlings (Table 4); however, the yield of 20-d-old seedlings at 5 hill^{-1} was lower than that of 15-d-old seedlings at 3 hill^{-1}. Thus, only to a limited extent can the number of seedlings hill^{-1} be adjusted to increase the grain yield of older seedlings. Dibbling pregerminated seeds at 1 and 3 seeds hole^{-1} could not produce yields as high as that of 15-d-old seedlings under intermittent and continuous irrigation in South Sulewesi (Table 9). In Bali, adjusting N application as per crop demand using the leaf color chart produced similar yields for both 15- and 21-d-old seedlings. The addition of poorly decomposed rice straw compost at transplanting time adversely affected young seedlings more than older ones in West Java (Table 5). The addition of well-decomposed farmyard manure or compost did not affect the performance of young seedlings in East Java (Table 7). Further study is ongoing to evaluate the mutual effect of all the components of the SRI combined as a package and to test the relative influence of different components by using the "full SRI minus one component" design, that is, SRI – seedling age, SRI – wide spacing, etc.

Farmer-cooperators of the ICM project in Indonesia recognize well the benefits of the SRI in terms of reduced seed rate (from 25–40 to 10–15 kg ha^{-1}) and high grain yield. However, they think that 15-d-old seedlings are too fragile to handle and that 50% more labor time is required to carefully pull, separate, and transplant seedlings. It may be difficult to obtain labor in some provinces to handle young seedlings gently. Small young seedlings are easily damaged by flood in poorly drained fields. Farmer-cooperators fear that planting 1 seedling hill^{-1} is risky, especially at sites with frequent seedling damage by grasshopper or golden snail; in such situations, they observed many empty spots and low plant population because of insect damage, especially when replanting was not done to fill the missing hills. They noted a substantial savings in N fertilizer use when they adopted the LCC method for N topdressing. With more experience and time, they can learn to handle young seedlings better to reap the benefits of a low seed rate and high yield.

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Aerobic rice

Aerobic rice in northern China: opportunities and challenges

Wang Huaqi, B.A.M. Bouman, Dule Zhao, Wang Changgui, and P.F. Moya

Aerobic rice is a new way of cultivating rice that requires less water than lowland rice. It entails the growing of rice in aerobic soil, with the use of external inputs such as supplementary irrigation and fertilizers, and aiming at high yields. The main driving force behind aerobic rice is the increasing water scarcity, especially in northern China, which threatens the sustainability of lowland rice production. A group of first-generation elite aerobic rice varieties such as Han Dao 297, Han Dao 277, Han Dao 502, Han 58, Danjing 5, and Danjing 8 have been developed and released since the early 1990s. It is estimated that these varieties are currently grown on 140,000 ha in northern China, replacing traditional lowland rice in water-short irrigated areas and traditional upland crops (such as maize, soybean, cotton) in low-lying flood-prone areas. The adoption of aerobic rice is facilitated by the availability of efficient herbicides and seed-coating technologies. Case studies showed yields to vary from 4.5 to 6.5 t ha^{-1}, which is about double that of traditional upland varieties and about 20–30% lower than that of lowland varieties grown under flooded conditions. However, the water use was about 60% less than that of lowland rice, total water productivity 1.6 to 1.9 times higher, and net returns to water use 2 times higher. Aerobic rice requires less labor than lowland rice and can be highly mechanized. Further developments of aerobic rice need to concentrate on continued breeding and the development of sustainable and farmer-acceptable crop management strategies.

The majority of the world's rice is being produced under flooded lowland conditions. Of the roughly 147 million ha of rice land, 79 million ha are classified as irrigated lowland, 36 million ha as rainfed lowland, and 13 million ha as flood-prone (IRRI 1997). In these environments, rice is mostly grown in bunded, puddled fields under flooded conditions. In contrast, in the irrigated lowlands, the fields are kept continuously flooded with a well-controlled 2–10-cm depth of water, and the pattern of flooding in the rainfed and flood-prone areas is erratic and determined by rainfall and surface flood events. All three ecosystems, however, are characterized by predominantly anaerobic soil conditions. The remaining 19 million ha of the world's rice area are classified as "upland rice." In the uplands, rice is sown in nonpuddled fields without bunds, without irrigation, and without ponded water. The soil is aerobic throughout the growing season. Upland rice environments are very heterogeneous but a common characteristic is that water is a major yield-limiting factor, soils are often problematic (in terms of physical and chemical properties), soil erosion is frequently severe, and farmers are among the poorest, with little means to supply external inputs. In the late 1990s, average yields in the "aerobic" uplands were around 1 t ha^{-1}, which was much lower than the average of about 5 t ha^{-1} in the "anaerobic" irrigated lowlands (IRRI 1997).

Recently, however, developments are taking place in the breeding and cultivation of upland rice that lead to greatly increased potential yield. This entails the growing of rice in aerobic soil, but with the use of external inputs such as supplementary irrigation and fertilizers, and aiming at high yields. The target environments are lowlands where water is scarce and the more favorable uplands. In China, developments in this new way of growing rice started in the mid-1980s. To differentiate it from the traditional upland rice, IRRI recently coined the term "aerobic rice": high-yielding rice grown in nonpuddled and nonflooded aerobic soil (Bouman 2001). In China, the term "Ju Dao" refers to all rice grown under upland or aerobic conditions, whereas the term "Han Dao" specifically indicates the new system of high-yielding aerobic rice. This paper reports on the current status of aerobic rice in northern China. It is divided into two parts: the first gives a broad overview of the geographical extent, the driving forces behind the development of aerobic rice, and the breeding strategy and general cultivation practices in northern China, and the second gives the initial results of two case studies on the testing of aerobic rice by farmers.

Aerobic rice in China

Extent and distribution

China has 31 million ha under rice cultivation (China Agricultural Almanac 2000). Since aerobic rice is not an officially recognized "crop type" yet, it does not appear in agricultural statistics. In March 2000, however, the China National Aerobic Rice Network (CNARN) organized a national Aerobic Rice Conference and got various experts to estimate the extent and distribution of traditional upland and aerobic rice in China. These estimates are based on individual spot checks in the field, inquiries with county-level agricultural bureaus and townships, and various unpublished data. It was estimated that about 120,000 ha are cropped to traditional upland rice and about 190,000 ha to aerobic rice. Traditional upland rice is mostly grown in the south and southwest of China, where Yunnan Province has the largest area of about 100,000 ha (Jiangsu Agricultural Science Academy 1986). At the CNARN meeting, the aerobic rice area was classified into four major ecosystems, based on geography, climate, and cropping patterns (Fig. 1):

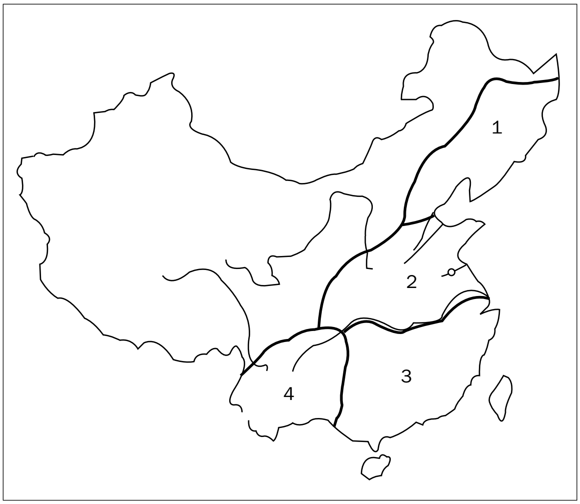

Fig. 1. Classification of the aerobic rice systems in China.

1. Northeast China single-cropping region (60,000 ha)
2. The Huang-Huai-Hai Plain double-cropping region (80,000 ha)
3. The South China hilly region for spring or summer cropping (30,000 ha)
4. The southwest mountain single-cropping region (20,000 ha)

The first two regions belong to the temperate north of China and the last two to the (sub-)tropical south of China. In this paper, we concentrate on the temperate northern areas.

The northeast China single-cropping region is very cold, with a short frost-free period (120–180 d) and little precipitation of 500–700 mm annually. Aerobic rice is mostly grown on the low-lying plains at 50–200 m above sea level. It can only be cropped one time per year in a short summer season of about 100–130 d duration. It is sown in the last 10 days of April and the first 10 days of May and harvested in mid-September to the beginning of October. The most important summer crops in this region are maize, spring wheat, and soybean.

The Huang-Huai-Hai Plain region lies in the warm temperate zone and is composed of the plains of the Yellow River, the Huai River, and the Hai River at 50–100 m above sea level. This region is cold in winter and hot in summer. Its annual rainfall ranges from 600 to 1,000 mm. Aerobic rice grows in summer and early autumn and is rotated with winter wheat or rape. It is sown within 3 weeks after the harvest of wheat or rape in late May or early June and matures by the end of September or early October. The most important summer crops in this region are maize, soybean, and cotton.

In both these regions, aerobic rice is planted in low-elevation plains where the land is flat, the soils are deep, the sunlight abundant, and the temperature difference between day and night large. About 70–80% of annual rainfall falls in the summer (aerobic rice) season, notably in June to September (Kerang Li and Shuying Xu 1990).

Because of the uneven distribution of rain, however, droughts occur frequently. Therefore, summer crops such as aerobic rice need supplemental irrigation. In the Huang-Huai-Hai Plain, short periods of flooding caused by heavy rainfall occur frequently in summer or in autumn.

Water: the driving factor for aerobic rice

The single most important driving force behind the current development and adoption of aerobic rice is the increasing shortage of water. China is one of the 13 countries with the least water resources in the world. The water availability per capita is only 2,230 m^3, which is about 25% of the world's average. In northern China, water availability is only 747 m^3 per capita and 7,065 m^3 ha^{-1}, which is only 21% and 10%, respectively, of the values in southern China (Liu Changming and He Xiwu 1996). Water shortage is especially severe in the Huang-Huai-Hai Plain. Surface-water and groundwater resources are overdrawn, leading to lowering of groundwater tables, formation of sink holes, diminished river flows, and heavy pressure on irrigated agriculture (Shu Geng et al 2001). Lowland rice is the single biggest water user in agriculture. In Asia, more than 50% of all water used for irrigation is used to irrigate rice (Barker et al 1999). Rice requires so much water because of the typical wet-land preparation (puddling) and the large losses by seepage, percolation, and evaporation from the ponded water layer. Typical values of water use in lowland rice are 1,000–2,000 mm, depending on soil type, water control, and hydrological conditions (Bouman 2001, Tuong and Bouman 2002). Tuong and Bouman (2002) estimated that some 4.5 million ha of irrigated rice area in northern China will likely experience "physical water scarcity" (insufficient water for agriculture regardless of cost) by 2025. Therefore, there is an urgent need for rice production systems that require less water. Aerobic rice grows in nonpuddled, nonflooded soil and has much less water requirement than lowland rice. In general, the use of irrigated water can be less than 50–70% of that normally used in lowland rice and the productivity of irrigation water (g grain kg^{-1} water) can be 2–3 times the value of that of lowland rice (Table 1). More empirical data are given by Yang et al (this volume) and in the second part of this paper. Because of the lower water requirement and higher water productivity, farmers are adopting aerobic rice in two kinds of water-short areas in northern China:

- Irrigated areas where water has become so scarce or expensive that lowland rice cannot be maintained anymore. At the 2000 CNARN Aerobic Rice Conference, it was estimated that aerobic rice can replace lowland rice on some 1.3 out of the 4 million ha of water-short lowlands in the coming decades (unpublished information).
- Rainfed areas where rainfall is insufficient to allow lowland rice production, but sufficient for aerobic rice. Maize and soybean are often the dominant summer crops and aerobic rice is an attractive alternative through the benefits of crop diversification. Moreover, the price of rice is supported by the government, which is perceived by farmers as advantageous.

Table 1. Typical yields and irrigation water amounts in lowland and aerobic rice in northern China (unpublished data; expert estimates from the 2000 CNARN Aerobic Rice Conference in Beijing, China).

Cropping pattern	Rice type	Irrigation frequency (y^{-1})	Irrigation amount (mm)	Yield (t ha^{-1})	Irrigation water productivity (g grain kg^{-1} water)
Single rice	Lowland rice	12–15	1,500	7.5	0.5
	Aerobic rice	4–5	375	6.0	1.6
Wheat-rice	Lowland rice	7–12	1,200	7.5	0.6
	Aerobic rice	2–3	225	5.3	2.3

Uncontrolled flooding is the second major driving force behind the adoption of aerobic rice. In the water-short Huang-Huai-Hai Plain, for example, Kerang Li and Shuying Xu (1990) reported that heavy rainfall and overflowing rivers cause temporary floods and waterlogging once every 1.5 years, and that the affected (disaster) area makes up 46% of the total flooded area of the whole of China. They further estimated that more than 10 million ha of upland crops such as maize and soybean suffer from waterlogging in northern China each year. The yield of maize without waterlogging, for instance, is on average 5.2–7.5 t ha^{-1}, but annual floods reduce the mean yields to 3.0–3.5 t ha^{-1}, while complete crop failure may occur in some areas. In addition, provincial statistics suggest that, at present, more than 660,000 ha of land are not being used during summer because of waterlogging, or even lie idle year-round (CAU, unpublished data). However, since aerobic rice can withstand flooding (e.g., Yang et al, this volume), these flood-prone areas are fit for growing aerobic rice. With an estimated yield of 4.5–6.0 t ha^{-1}, aerobic rice increases grain yield by about 1.5 t ha^{-1} compared with maize. The adoption of aerobic rice in northern China is now most rapid in these flood-prone areas. It is estimated that aerobic rice in these areas could be developed on some 3.3 million ha.

Varietal development

The breeding of aerobic rice for northern China has been pioneered by the China Agricultural University (CAU), the China Academy of Agricultural Sciences, the Liaoning Province Academy of Agricultural Sciences, and the Dandong Academy of Agricultural Sciences since the 1980s. From the mid-1980s to the early 1990s, some early aerobic rice varieties such as Qinai, Heda 77-2, Zhongyuan 1, Zhongyuan 2, and Han 72 were bred and released. These varieties showed improvements over local upland varieties by having early maturity, improved plant type, and responsiveness to fertilizer, which all led to higher yields. However, shortcomings such as vulnerability to rice blast, a weak ability of the seedlings to emerge through the soil surface, and low vegetative vigor limited their widespread adoption. Moreover, a vigorous growth of animal husbandry and fish production in those years stimulated the demand for maize. These factors led to the gradual disappearance of upland and aerobic rice from northern China. However, in the mid-1990s, the emerging water crisis and the continuous need to feed a still-increasing population renewed interest in aerobic rice.

The China Agricultural University (CAU) started its systematic aerobic rice breeding program in the early 1980s (Wang Huaqi and Wang Xiangkun 1989). This program is based on the genetic recombination of lowland and upland varieties from different eco-geographic origins. In 1984, a group of traditional upland rice varieties from Yunnan Province in the southwest of China and from neighboring countries such as Lao PDR and Thailand was crossed with a group of lowland varieties from northern China and Japan. Pedigree and bulk selection were applied to different progenies and populations in different generations. From 1985 to 1990, early generation material was grown in lowland environments for selection on plant architecture, and late-generation material was grown in aerobic environments for selection on drought tolerance. From 1989 to 1995, observation and identification trials were conducted using fixed-generation materials for specific ecoregion adaptability. This led to the development of a group of new-generation elite aerobic varieties such as Han Dao 297 from Mujiao 78-595 (L) + Khaoman (U), Han Dao 277 from Qiuguang (L) + BanLi 1 (U), and Han Dao 502 from Qiuguang (L) + Hongkelaoshuya (U) (where U = upland variety and L = lowland variety). These varieties have been released and disseminated to farmers in northern China since 1997. Meanwhile, other improved aerobic varieties such as Han 58 from the Liaoning Provincial Academy of Agricultural Science (Liaoning Academy of Agricultural Science 1993) and Danjing 5 and Danjing 8 from the Dandong Academy of Agricultural Sciences have been released to farmers in Liaoning Province, northeast China. Compared with the early aerobic rice varieties released in the 1980s, these new elite varieties show breakthroughs in traits such as stronger drought tolerance, reduced plant height, increased lodging resistance, erect upper leaves, higher yields, stronger resistance to blast, and better grain quality. Table 2 gives the yield and extent of distribution for some of these varieties in northern and northeastern China. Han Dao 277 and Han 58 are currently the most extensively grown varieties. Table 3 gives some performance indicators of the three Han Dao varieties released by CAU as observed at an experiment station and in some

Table 2. Current main aerobic rice varieties in northern and northeastern China in 2000 (unpublished data; expert estimates from the 2000 CNARN Aerobic Rice Conference in Beijing, China).

Variety	Yield (t ha^{-1})	Area (000 ha)	Distribution
Han Dao 277	5.25–6.0	47.0	Middle and lower reaches of Yellow River and north to Huai River
Han Dao 297	5.25–6.75	5.3	North China, southern part of northeastern China
Han Dao 65	4.5–5.25	13.3	Northern and northeastern China
Han 58	6.0–6.75	20.0	South of northeastern China
Danjing 5	6.0–6.75	6.7	South of northeastern China
Danjing 8	6.0–6.75	6.7	South of northeastern China

Table 3. General performance indicators of elite Han Dao aerobic rice varieties as observed from 1997 to 1999 in farmers' fields at Jining City in Shandong Province and in Xincai County, Henan Province, and at the Baoshan town agricultural extension station, Huairou County, Beijing, in northern China (unpublished CAU data).

Variety	Regions of adoption	Growth duration (d)	Yield (t ha^{-1})	Irrigation water (mm)	Yield record (t ha^{-1})
Han Dao 277	Huang-Huai-Hai Region	105–115	5.0–6.0	150–225	8.7
Han Dao 297	North China	130–140	5.0–6.5	225–375	8.25
Han Dao 502	Along Huai River and in Changjiang River valley	115–130	6.0–7.0	225–300	8.4

Table 4. Grain quality measures of Han Dao 297, as measured by the China Agricultural Ministry Food Quality Supervision and Test Center (Wuhan), 12 December 2001.

Item	Value		Standard value for class 1	Grading
	Sample 1[a]	Sample 2		
Milling recovery (%)	75.4	82.5	>81	First-second
Head rice (%)	59.2	69.8	>66	First-second
Chalky rice (%)	38.0	30.0	<10	Below third
Chalk (%)	3.8	3.0	<1	Second
Amylose content (%)	13.2	14.7	15–18	Second
Gel consistency (mm)	85	80	>70	First

[a]Sample 1 from national trial in Loaning and sample 2 from farmer's field at Hanjiachuan, Beijing.

farmers' fields in the late 1990s. Tables 2 and 3 show that rice yields of these new elite aerobic rice varieties are 5–7 t ha^{-1}, whereas maximum yields of 8 t ha^{-1} and higher have been recorded. The grain quality of some of these varieties, such as Han Dao 297, is graded 1 to 2 according to the national standard for (japonica) rice (Table 4).

Current management practices

In northern China, aerobic rice receives supplementary irrigation with a typical frequency of 2–5 times with application rates of 60–75 mm each (see also Table 1). The irrigation method is usually flash irrigation, though sometimes sprinklers are used, such as around Beijing. Fertilizer application rates have been higher in recent years than in the past, but are still moderate compared with those of lowland rice. Nitrogen is usually given at 113–150 kg ha^{-1}. The application rate of phosphorus and potassium is variable. In some places where zinc or iron is deficient, farmers have started to apply micronutrient fertilizers. In recent years, the use of chemical herbicides has become popular in China for all major crops. A few commercial herbicides such as Nongsita, Dingcaoan, Bendasong, Kuaishabai, and Xicaojing are used in aerobic rice. The use of these herbicides before or after seedling emergence plus additional manual weeding effectively keep weeds under control. Another recent innovation is "seed-coating." Seeds are immersed in a liquid mixture of different chemicals to prevent attacks from insects in the soil, and from birds and rodents, and to alleviate micronutrient deficiencies during the seedling stage. In most parts of northern China, farmers have adopted mechanical direct seeding (instead of manual seeding or using animal-drawn seeders) to save labor. We hypothesize that especially the availability of herbicides and the seed-coating technology, alongside the release of the new elite varieties, has accelerated the adoption of aerobic rice by farmers. The estimated area under Han Dao 277, for example, was 333 ha in 1998, 10,000 ha in 1999, and 47,000 ha in 2000 (unpublished data; expert estimates from the 2000 CNARN Aerobic Rice Conference in Beijing, China).

Case study of farmer testing of aerobic rice

Little to no systematic research has been done yet on the biophysical and socioeconomic performance of aerobic rice under farmer conditions. Therefore, the CAU and the International Rice Research Institute began a comparative study among farmers growing aerobic rice and lowland rice in northern China in 2001.

Materials and methods

Pilot sites were established near Beijing and in Guanzhuang village (Fengtai County, Anhui Province). Near Beijing, a farmer cooperative at Hanjiachuan grew aerobic rice Han Dao 297 on 9 ha. The soil was classified as loam to silty loam, with 29% sand, 50% silt, and 21% clay. Irrigation was applied using a movable sprinkler system drawing water from a deep well. The crop was mechanically sown on 17 May and combine-harvested on 15 October. For comparison, a 0.3-ha lowland rice field at Changle (some 5 km away from Hanjiachuan, but experiencing the same agroecological conditions) planted with lowland rice Jin Dao 305 was included in the study. This field got its water by pumping from a small reservoir. Except for a few areas, the government has forbidden the growing of lowland rice around Beijing as of 2001 as a response to the increasing water scarcity. Farmers are therefore interested in exploring aerobic rice as an alternative.

Guanzhuang lies in the Yongyin irrigation system, which gets its water from the Huai River. Being at the tail-end of the system, water is relatively scarce and farmers are increasingly abandoning lowland rice production. In 2001, 10 farmers tried aerobic rice on 4 ha originally planned to be left fallow because of the water shortage. The crop was mechanically sown on 15 June and harvested on 5 October. Irrigation was applied by flash flooding using water pumped from a small reservoir fed by the irrigation system. Three farmers were selected who grew aerobic rice and who also grew lowland rice in fields surrounding the aerobic rice land. The aerobic rice variety was Han Dao 502 and the conventional lowland varieties were the hybrids 65002 and

Xieyou 63 and the inbred Yikenuo. The soil was similar to that near Beijing, with 35% sand, 48% silt, and 16% clay. At both sites, the farmers recorded all the activities, labor use, and input use in each of their fields. Prices of all inputs and of rice were collected. At each irrigation, the start and finish time of water delivery was recorded. The amount of irrigation water applied was estimated by multiplying the irrigation duration with the flow rate of the pump. Rain gauges were installed at the sites. During the season, groundwater table depths were measured daily in the aerobic rice plots. Total yield of each field was recorded after harvest.

First-year results

Table 5 summarizes the results. Recorded rainfall during crop growth was 337 mm at Changle, 299 mm at Hanjiachuan, and only 70 mm at Guanzhuang, where this amount was the least of the last 100 years. The groundwater depth under the aerobic rice fields at Hanjiachuan was mostly deeper than 180 cm, except for a peak period in late August-early September, when it came up to 30 cm and quickly receded below 120 cm in about 10 days. At Guanzhuang, the groundwater depth fluctuated mostly from 40 to 120 cm and dipped below 180 cm for some days in late July.

At Guanzhuang, the yield of Han Dao 297 varied from 4.6 to 6.6 t ha^{-1}, with total water input varying from 608 to 620 mm (for the three monitored fields). At Beijing, the total yield of the whole 6 ha was 4.6 t ha^{-1} but we do not know the range in variability. Compared with the situation at Beijing, the aerobic rice at Guanzhuang

Table 5. Mean biophysical and socioeconomic performance indicators of aerobic rice and lowland rice produced by farmers at Guanzhuang and near Beijing.

Location	Guanzhuang		Beijing	
Rice type	Aerobic	Lowland	Aerobic	Lowland
Yield (t ha^{-1})	5.8	7.9	4.6	7.1
Irrigation (mm)	542	1,291	177	1,057
Total water (mm)	612	1,361	476	1,394
Total water productivity (g kg^{-1})	0.95	0.58	0.96	0.51
Irrigation water productivity (g kg^{-1})	1.07	0.61	2.58	0.67
Production value ($ ha^{-1})	868	1,016	1,058	1,633
Paid-out costs ($ ha^{-1})	343	292	322	565
Imputed family labor costs ($ ha^{-1})	87	171	39	165
Total costs ($ ha^{-1})	430	463	361	730
Gross margin[a] ($ ha^{-1})	525	724	736	1,068
Net return[b] ($ ha^{-1})	438	553	697	903
Family labor use (8-h labor-day ha^{-1})	46	90	12	53
Net returns to water ($ m^{-3})	0.0715	0.0406	0.1464	0.0648
Price of grain ($ kg^{-1})	0.15	0.13	0.23	0.23
Price of labor ($ d^{-1})	1.9	1.9	3.1	3.1

[a]Calculated as production value minus paid-out costs. [b]Calculated as production value minus paid-out costs minus family labor costs.

received more water and was grown with shallower water tables (that may have supplied extra water to the crop by capillary rise). This may help explain why yields were higher at Guanzhuang than at Beijing. On average, the yield of aerobic rice was 27% and 35% lower than that of lowland rice at Guanzhuang and Beijing, respectively. However, water use was 55% and 66% lower in aerobic rice than in lowland rice at Guanzhuang and Beijing, respectively. Since the reduction in water use was relatively larger than the reduction in yield, the water productivity (g grain kg^{-1} of total water used) of aerobic rice was 1.6 and 1.9 times higher than that of lowland rice at Guanzhuang and Beijing, respectively.

On the socioeconomic side, there were considerable differences in net returns and gross margins between aerobic and lowland rice at the two sites. Net returns to aerobic rice cropping (on a per hectare basis) were 26% and 30% lower than those to lowland rice cropping at Guanzhuang and Beijing, respectively. This could be attributed to the lower yields of aerobic rice compared with those of lowland rice. However, again because of its much lower water use, the net returns per unit of water used were on average twice as high in aerobic rice as in lowland rice. At both sites, the use of family labor was much less in aerobic rice than in lowland rice: 47% less at Guanzhuang and 77% less at Beijing. This is mainly because lowland rice requires much labor for wet-land preparation, transplanting, and irrigation activities. This lower labor requirement of aerobic rice would then give more time to the family to work outside the farm for additional sources of income. At both sites, the farmers were very satisfied with the results from aerobic rice cropping. On their aerobic rice fields, they did not have the option of growing lowland rice because of the water shortage (Guanzhuang) or government restrictions (Beijing).

Conclusions and future directions

After a systematic breeding program of 20 years, a first generation of aerobic rice (Han Dao) varieties has been developed, with yields ranging from 4.5 to close to 7 t ha^{-1} under farmer and experimental conditions. This is a great improvement over traditional upland rice varieties, with typical yields of 1.5 to 3.0 t ha^{-1}, such as Hanjingzi in Hebei Province and Hongkelaoshuya (male parent of Han Dao 502) in Yunnan Province. Compared with lowland production systems (modern high-yielding lowland varieties under fully flooded conditions), aerobic rice (aerobic rice varieties in aerobic conditions) yields 30% less. However, the water use in aerobic rice, as measured in our case studies, was about 60% less than that in lowland rice, so that total water productivity was 1.6 to 1.9 times higher. Though the net economic returns per hectare were lower, the net returns in monetary units per unit of water used were 2 times higher in aerobic rice than in lowland rice. All these results indicate that, with the current varieties, aerobic rice is an attractive alternative to lowland rice in areas where water is the limiting factor rather than land (in a physical or economic sense). The potential target domain for aerobic rice is large and extends beyond China. Tuong and Bouman (2002) calculated that, of all irrigated rice areas, about 4.5 million ha in northern China, 2.1 million ha in Pakistan, and 10.4 million ha in northern and central

India will probably experience physical water scarcity by 2025. In addition, approximately 22 million ha of irrigated rice in South and Southeast Asia will suffer from "economic water scarcity" (prohibitively high water prices for agriculture) by that time.

However, the concept of aerobic rice is still in its infancy and much work needs to be done. There are major challenges in two areas:

Breeding

Though systematic breeding has been done for about 20 years, the Chinese breeding program was extremely small compared with breeding efforts being made in lowland rice. The genetic basis is still very narrow and only a few successful aerobic rice varieties exist. Further efforts need to be directed at increasing the yield potential and looking at broad biotic (diseases, weeds) and abiotic (drought, micronutrient deficiency) stress tolerances. Besides yield, grain quality should be a key focus of attention since this will determine consumer acceptability. Different varieties need to be developed for particular agroecological target domains (e.g., the four major zones distinguished in China).

Crop management and cropping systems

Little is known about optimum management practices for aerobic rice in terms of water and nutrients. Since the water shortage is the main driving force for the development of aerobic rice, special attention should be given to understanding crop-water relationships and trade-offs between yield and water use. The potential of aerobic rice to withstand periods of flooding should also be further studied and quantified since this is a major advantage of aerobic rice compared with other upland crops such as maize or soybean. Compared with flooded lowland conditions, weeds pose a bigger threat in aerobic soils, and more environmentally friendly ways of controlling weeds than the sole use of herbicides should be investigated. Little to nothing is known about the long-term sustainability of aerobic rice. There is evidence in Brazil that yields decline dramatically after three to four years of monocropping (Guimarães and Stone 2000). Similar yield declines under continuous upland rice cropping have also been documented in the Philippines by George et al (2002), who speculate that this decline, which cannot be reversed with inorganic fertilizers, may be related to the buildup of soil pathogens or to micronutrient disorders. Farmers in northern China are now advised not to continuously crop aerobic rice on the same piece of land until this problem is better understood and remedies proposed. Appropriate cropping systems and crop rotations need to be developed that guarantee long-term sustainability, fit in current production systems, and are farmer-acceptable.

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Yield of aerobic rice (Han Dao) under different water regimes in North China

Yang Xiaoguang, Wang Huaqi, Wang Zhimin, Zhao Junfang, Chen Bin, and B.A.M. Bouman

Lowland rice in Asia has relatively high water inputs. Because of increasing water scarcity, there is a need to develop alternative systems that require less water, especially in northern China, where water shortages are acute. "Aerobic rice" is high-yielding rice grown in nonpuddled aerobic soils under supplementary irrigation. Special aerobic rice varieties, called Han Dao, have been developed by the China Agricultural University. Field experiments began in 2001 to determine the yield potential of these varieties under different irrigation regimes. In one experiment, aerobic varieties Han Dao 297 (HD297) and Han Dao 502 (HD502) and lowland variety Jin Dao 305 (JD305) were grown in aerobic soil under five irrigation regimes. In a second experiment, the same varieties were grown under flooded lowland conditions. Under flooded lowland conditions, the total water input (irrigation plus rainfall) was about 1,400 mm. Lowland variety JD305 recorded the highest yield (8.8 t ha^{-1}) and the yields of HD502 and HD297 were 6.8 and 5.4 t ha^{-1}, respectively. Under aerobic conditions, the total water input varied from 470 to 644 mm. The aerobic varieties outyielded the lowland variety. With 470 mm water, HD297 yielded 2.5 t ha^{-1}, HD502 3.0 t ha^{-1}, and JD305 1.2 t ha^{-1}; with 644 mm water, HD502 and HD297 yielded 5.3 and 4.7 t ha^{-1}, respectively, while JD305 yielded 4.2 t ha^{-1}. The water-use efficiencies of the aerobic varieties under aerobic conditions were 164–188% higher than that of the lowland variety under lowland conditions. Aerobic rice maximizes water use in terms of yield and is a suitable crop for water-limiting conditions.

Rice is the most important cereal crop in Asia (IRRI 1997). In China, it is also the crop with the largest planted area and the highest productive output (FAO 2002). But traditional lowland rice with continuous flooding has relatively high water inputs (Bouman 2001) and its sustainability is threatened by increasing water shortages. China is one of 13 water-short countries in the world, with 2 billion m^3 total water resources and 2,200 m^3 per capita water availability (Liu Changming and He Xiwu 1996). Water is especially scarce in northern China, where per capita water availability is only 700 m^3. The North China Plain contains 26% of China's cultivated land, 30% of the irrigated land, and 24% of the total grain production (Shu Geng et al 2001). Rainfall is barely sufficient to support a one-season crop and grain production relies heavily on irrigation. However, since the Plain also contains 24% of China's population and supports large cities and industry, competition for scarce water is severe. Surface-water and groundwater resources are overdrafted, leading to diminished river flows and lowering of groundwater tables (Shu Geng et al 2001). To ensure food security and sustain the agricultural sector, there is a need to develop water-saving agricultural practices. Aerobic rice is a new concept of growing rice: it is high-yielding rice grown in nonpuddled aerobic soil under supplementary irrigation. Recently, special aerobic rice varieties, called Han Dao, have been developed by the China Agricultural University (CAU) and are being commercially grown by farmers in northern China. However, little is known about the optimum management practices to save water while obtaining high yields. Insights into the basic crop-water relationships to optimize irrigation water management are lacking. Therefore, the CAU and the International Rice Research Institute (IRRI) began field experiments in 2001 to determine the yield potential of aerobic rice varieties under different irrigation regimes and to establish basic crop-water response functions. This paper reports on the first results of these field experiments.

Materials and methods

A field experiment was carried out from April to October 2001 at Changping Experiment Station (40°02′N, 116°10′E; elevation of 43.0 m) of the China Agricultural University, near Beijing. Some soil properties are given in Table 1.

Table 1. Soil properties at Changping as measured in our experimental fields in 2001.

Physical properties[a]		Chemical properties[b]					
Texture	Bulk density (g cm^{-3})	Total N (%)	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	SOM[c] (%)	pH
53–57% sand, 36–40% silt, 6–7% clay	1.44	0.13	114	55	125	1.59	7.8

[a]From 0–50-cm depth. [b]From 0–20-cm depth. [c]SOM = soil organic matter.

Three varieties were grown: two aerobic varieties, Han Dao 502 (HD502) and Han Dao 297 (HD297), and one popular lowland variety, Jin Dao 305 (JD305). Five water treatments were imposed to create a range in soil water conditions in the vegetative and reproductive stages of crop growth: soil water content in the root zone at 80–90% throughout the growing season (W1), at 60–70% from emergence till panicle initiation (PI) and 80–90% from PI onward (W2), at 80–90% from emergence until PI and 60–70% from PI onward (W3), at 60–70% throughout the growing season (W4), and rainfed rice with "survival" irrigation at visual symptoms of severe drought stress (W5) (since PI was not directly observed in the field, the "jointing stage"—defined as the start of stem elongation when the first internode is 1 cm—was used as a proxy). The experiment was laid out in a randomized block design with four replicates. Plot sizes were 6×10 m^2. Plots were bunded to check the flush irrigation and separated by 1-m-wide strips of bare soil. Crop establishment was by hand dibbling at 3-cm depth in rows 30 cm apart, at 150 kg ha^{-1} for HD502 and JD305 and 120 kg ha^{-1} for HD297. The seeding rate for the Han Dao varieties was lower since they were expected to have less tillering capacity. To synchronize flowering time (to avoid yield differences caused by asynchronous heat damage at flowering), the three varieties were sown at different dates: HD502 and JD305 on 25 April and HD297 on 16 May. Nitrogen application was 200 kg ha^{-1}, of which 50% was applied at sowing, 25% about 1 month after emergence, and 25% at booting. At sowing, 56 kg ha^{-1} of P_2O_5 and K_2O, 22.5 kg ha^{-1} of iron sulfate, and 15 kg ha^{-1} of zinc sulfate were applied. Before the start of the experiment, on 3 April, the area had received (unplanned) dry chicken manure and carbamide with an N-P_2O_5-K_2O equivalent of 120-52-45 kg ha^{-1}. The plots were kept weed-free by an application of preemergence herbicide and hand weeding after crop establishment. Pesticides were applied as appropriate for good crop protection. Irrigation was applied through flexible hoses connected to a subsurface pressurized pipe system drawing water from a deep groundwater well. Daily weather data were acquired from the experimental station's weather station. In addition, rainfall and evaporation were measured in the field experiment by a standard rainfall meter and evaporation pan, respectively. The depth of the groundwater table was observed in a nearby observation well. Irrigation water input was measured with calibrated flow meters connected between the flexible hoses and the pressurized pipe system. Biomass and grain yield (12–14% moisture content) were recorded from harvested areas of about 57 m^2 of each plot.

A separate trial was established to estimate the yield potential of the three varieties under fully flooded conditions. The location was Changle in Shangzhuang village (Haidian District of Beijing), about 5 km away from Changping and presumably experiencing the same weather conditions. This trial was executed at a different location because the growing of flooded rice was forbidden in the Changping area by the government as of 2001. The crops were transplanted in hills spaced at 13×27 cm, in plots of 6×10 m^2 without replication. Each variety was established to synchronize flowering time as best as possible: JD305 was transplanted on 25 May, HD502 on 1 June, and HD297 on 7 June. Fertilizer N was given as 60 kg ha^{-1} at transplanting, 90 kg ha^{-1} 7 days after transplanting, and 38 kg ha^{-1} at booting. At transplanting, 30 and

60 kg P_2O_5 and K_2O ha^{-1} were given, respectively. The plots were kept permanently flooded except for a 7–10-day midseason drainage period. Biomass and grain yield (12–14% moisture content) were recorded from harvested areas of about 57 m^2 of each plot. The irrigation water input was estimated from the pump operation time.

Results

Table 2 gives the weather data as measured during the crop-growing season at Changping.

Crop growth and yield

The phenological development of the crops is given in Table 3. Table 4 gives the yield and yield components of the crops at Changle and Table 5 those of the crops at Changping.

Under flooded conditions at Changle, lowland variety JD305 recorded the highest yield; the yield of HD502 was 23% lower and that of HD297 39% lower than that of JD305. The differences in yield were correlated with the differences in growth duration (r^2 = 99%): JD305 had the longest growth duration and the highest yield and HD297 had the shortest growth duration and the lowest yield (Fig. 1).

Under aerobic conditions at Changping, all three varieties yielded lower than under flooded conditions at Changle. The two aerobic varieties yielded higher than the lowland variety. In all water treatments, HD502 yielded the highest and JD305 the lowest. The yield of HD502 was higher than that of HD297 because it had an 18–20-day longer growth period. However, the relationship between growth duration and yield broke down with lowland variety JD305 (Fig. 1).

Table 2. Observed weather data during the 2001 cropping season at Changping.

Month	Daily average			Monthly total	
	Solar radiation (MJ m^{-2})	Minimum temperature (°C)	Maximum temperature (°C)	Rain (mm)	Pan evaporation (mm)
Jan	7.0	–9.5	–1.1	8	na[a]
Feb	9.7	–6.3	4.4	2	na
Mar	16.1	0.9	14.0	0	na
Apr	17.1	8.5	20.7	14	na
May	21.2	16.6	30.4	4	465
Jun	16.6	20.7	31.2	56	240
Jul	17.7	22.4	32.9	92	192
Aug	17.5	20.2	30.4	217	149
Sep	15.4	15.5	26.7	13	136
Oct	9.5	8.9	19.1	34	75
Nov	9.2	0.8	11.4	18	na
Dec	6.9	–5.8	1.7	1	na

[a]na = not available.

Table 3. Phenological development (measured at 50% value) of the crops at Changping and Changle. For Changping, the dates are the ranges from the five water treatments.

Changping (aerobic)	Sowing	Emergence	Jointing[a]	Flowering	Maturity	Duration (d)[b]
HD502	25 April	12 May	24-27 July	13-20 Aug.	6-10 Oct.	150–154
HD297	16 May	24 May	22-25 July	17-24 Aug.	2-4 Oct.	132–134
JD305	25 April	12 May	3-6 Aug.	31-Aug.-5 Sep.	16-18 Oct.	160–162
Changle (flooded)	**Sowing**	**Transplanting**	**Jointing[a]**	**Flowering**	**Maturity**	**Duration (d)[b]**
HD502	13 May	1 June	7 July	14 August	6 Oct.	147
HD297	25 May	7 June	7 July	7 August	30 Sep.	129
JD305	29 April	25 May	10 July	30 August	10 Oct.	165

[a]Jointing is the start of stem elongation (when the first internode is 1 cm), taken as a proxy for panicle initiation, which was not directly observed. [b]Duration is calculated as the number of days from emergence to maturity.

Table 4. Yield (from 57-m^2 area) and yield components (from 50-stem subsample) of the flooded experiment at Changle station.

Variety	Panicles m^{-2}	Filled grains $panicle^{-1}$	% filled grains	1,000-grain weight (g)	Yield (t ha^{-1})
HD502	232	102	86	31	6.8
HD297	240	87	89	29	5.4
JD305	342	126	96	22	8.8

The yield of JD305 declined relatively more severely with decreasing water input than that of the two aerobic varieties. The variety × water interaction was statistically significant at the 1% level. Compared with flooded conditions, the number of panicles m^{-2} was significantly higher (7–15%) under aerobic conditions for the aerobic varieties, but 7% lower for the lowland variety (except for treatment W1). The number of filled grains $panicle^{-1}$ was lower under aerobic conditions than under flooded conditions for all three varieties, but the difference was especially large for the lowland variety (11–17% for the aerobic varieties, 41% for the lowland one). The percentage of filled grains was only slightly lower under aerobic conditions than under flooded conditions for the two aerobic varieties (3–11%), but much lower for the lowland variety (37%). Finally, the grain weight of HD502 was the same under aerobic and flooded conditions, but it was on average 9% and 15% lower under aerobic conditions for HD297 and JD305, respectively. The yield that is calculated from the yield components (derived from the 30-stem subsample) is on average 30–40% higher than the yield obtained from the whole plot. This is explained by the relatively high harvest loss for the whole plot (machine harvest) and by a bias to select better-looking areas in a plot for sampling. With decreasing water supply under aerobic conditions, all three varieties had decreasing numbers of panicles m^{-2}, filled grains $panicle^{-1}$,

Table 5. Yield (from 57-m^2 area) and yield components (from 50-stem subsample) of the aerobic experiment at Changping station (mean values and ± standard deviation).

Variety	Treatment	Panicles m^{-2}	Filled grains $panicle^{-1}$	% filled grains	1,000-grain weight (g)	Yield (kg ha^{-1})
HD502	W1	295 ± 31	91 ± 13	88 ± 1	32.1 ± 0.5	5,338 ± 268
	W2	267 ± 40	89 ± 6	87 ± 2	31.5 ± 0.8	4,618 ± 218
	W3	282 ± 43	82 ± 10	82 ± 3	30.6 ± 0.5	4,268 ± 224
	W4	251 ± 23	84 ± 7	79 ± 3	29.2 ± 0.2	3,478 ± 313
	W5	239 ± 9	78 ± 9	82 ± 5	30.1 ± 0.4	3,043 ± 224
HD297	W1	274 ± 39	80 ± 10	83 ± 7	28.9 ± 1.2	4,710 ± 278
	W2	251 ± 62	83 ± 11	82 ± 3	27.7 ± 1.0	4,338 ± 105
	W3	259 ± 30	81 ± 9	83 ± 1	25.9 ± 0.7	4,173 ± 58
	W4	257 ± 24	80 ± 14	84 ± 3	25.5 ± 0.4	3,381 ± 510
	W5	240 ± 21	62 ± 11	63 ± 8	23.4 ± 0.8	2,547 ± 462
JD305	W1	400 ± 27	104 ± 17	84 ± 5	20.8 ± 0.4	4,235 ± 321
	W2	254 ± 75	97 ± 20	83 ± 2	19.6 ± 0.5	3,767 ± 340
	W3	326 ± 47	101 ± 27	74 ± 8	19.4 ± 0.3	1,995 ± 636
	W4	321 ± 32	59 ± 13	50 ± 10	18.5 ± 0.5	1,494 ± 256
	W5	288 ± 23	70 ± 32	31 ± 11	15.2 ± 1.3	1,205 ± 297
LSD[a] variety		ns[b]	19	17	0.8	393
LSD treatment		ns	22	9	1.4	499
LSD interaction		83	54	ns	2.28	1,335

[a]LSD = least significant difference at 0.05 significance level. [b]ns = not significant.

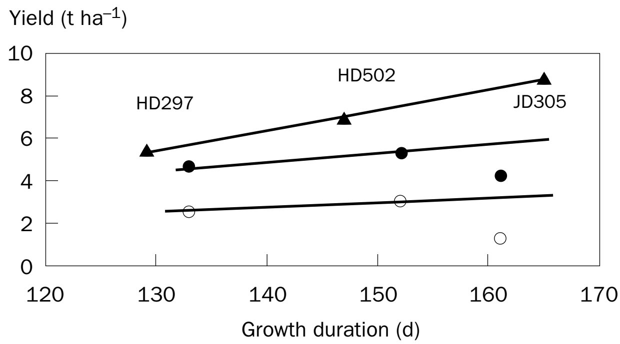

Fig. 1. Yield versus growth duration of the three varieties under flooded conditions (▲ with solid trend line) in aerobic treatment W1 (●) and in aerobic treatment W5 (○).

percentage filled grains, and grain weights. The differences, however, were only statistically significant for grain weight for all three varieties, and for filled grains panicle^{-1} and percentage filled grains for lowland variety JD305.

Water use

The rainfall between sowing and harvest was 294 mm at Changping and 337 mm at Changle. The total irrigation water inputs at Changping are given in Table 6. At Changle, the total amount of irrigation water applied was 1,057 mm for all three varieties. At Changping, the groundwater depth was on average 21 m, while at Changle it fluctuated from 0 to 0.4 m. Water-use efficiency (WUE), calculated as the amount of grain (yield) produced per unit water input from sowing to harvest, is given in Table 7 (note: in this definition, WUE is the same as water productivity).

Table 6. Irrigation water application (mm) per treatment at Changping.

Water treatment	From sowing to PI[a]	From PI to maturity	From sowing to maturity
W1	200	150	350
W2	133	150	283
W3	200	92	292
W4	133	92	225
W5	125	50	175

[a]PI = panicle initiation.

Table 7. Water-use efficiency (g grain kg^{-1} water) at Changping and Changle.

Treatment	HD502		HD297		JD305	
	WUE_I[a]	WUE_{R+I}[b]	WUE_I	WUE_{R+I}	WUE_I	WUE_{R+I}
Changping						
W1	1.53	0.83	1.35	0.73	1.21	0.66
W2	1.63	0.80	1.53	0.75	1.33	0.65
W3	1.46	0.73	1.43	0.71	0.68	0.34
W4	1.55	0.67	1.50	0.65	0.66	0.29
W5	1.74	0.65	1.46	0.54	0.69	0.26
Changle	0.64	0.50	0.51	0.40	0.83	0.65

[a]WUE_I is water-use efficiency with respect to irrigation water. [b]WUE_{R+I} is water-use efficiency with respect to irrigation plus rainfall.

The total amount of irrigation and rainfall input during crop growth (excluding the 105 mm for land preparation) was much lower in the aerobic plots at Changping (470–586 mm) than in the flooded plots at Changle (1,351 mm). This is not only an "aerobic" versus a "flooded" cultivation effect since hydrological (groundwater) conditions were also different. However, it does show that aerobic rice can be grown using a small amount of water only.

Under flooded conditions, the lowland variety had higher WUEs than the two aerobic varieties because it had a higher yield. Under aerobic conditions, however, the aerobic varieties had higher WUEs than the lowland variety in all water treatments. As with yield, aerobic variety HD502 had higher WUEs than HD297. In all water treatments of the aerobic conditions, the WUEs of both HD502 and HD297 were higher than those of JD305 under flooded conditions.

Conclusions and discussion

The especially bred aerobic rice varieties Han Dao 502 and 297 performed well under supplementary-irrigated aerobic conditions. With as little as 470 mm of total water, HD297 still yielded 2.5 t ha^{-1} and HD502 3.0 t ha^{-1}, whereas, with 650 mm, they yielded 4.7 and 5.3 t ha^{-1}, respectively. The higher yield of HD502 may be explained by its 18–20-d longer growth duration. In contrast, despite a growth duration of 8–10 d longer than that of HD502, the yield of lowland variety JD305 was much lower under aerobic conditions: only 1.2 t ha^{-1} with 470 mm and 4.2 t ha^{-1} with 650 mm of total water. This demonstrates that special breeding programs are required to develop aerobic rice varieties. With a decreasing amount of water application, all investigated yield components decreased as well, though the effect was statistically significant only for grain weight for all three varieties, and for filled grains $panicle^{-1}$ and percentage filled grains for the lowland variety.

The tested aerobic rice varieties had good yields of 5.4 t ha^{-1} (HD297) and 6.8 t ha^{-1} (HD502) under lowland conditions, demonstrating their flood tolerance. The lower yields compared with that of the lowland variety (8.8 t ha^{-1}) correlated well with their shorter growth durations. Therefore, the physiology of yield formation under flooded conditions may be the same for the aerobic varieties and the lowland variety.

Compared with lowland conditions, the water used by aerobic rice in our study was more than 50% lower. The water-use efficiencies of the aerobic rice varieties under aerobic conditions were much higher (164–188%) than that of the lowland rice variety under lowland conditions. This means that aerobic rice maximizes water use in terms of yield and is a suitable crop for water-short and water-costly conditions. The relatively high water-use efficiencies for irrigation water are an especially important consideration for irrigation managers and agricultural planners.

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The potential of aerobic rice to reduce water use in water-scarce irrigated lowlands in the tropics

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Water scarcity in Asia threatens the sustainability of traditional flooded lowland rice systems and ways must be sought to grow rice using less water. A promising new cropping system is "aerobic rice," which is rice grown in nonflooded and nonpuddled soil using supplementary irrigation. In 2001, a field experiment was undertaken at the International Rice Research Institute to characterize the hydrology and compare the yield and water use of rice grown under aerobic and under flooded conditions, using different upland varieties and one hybrid rice variety. The aerobic plots were irrigated up to field capacity when soil water tension at 15-cm depth reached 30 kPa.

Yields under aerobic conditions were 2.4–4.4 t ha^{-1}, which were 14–40% lower than under flooded conditions. The total water input from transplanting to harvest was 650–830 mm under aerobic conditions and about 1,350 mm under flooded conditions. Because water use decreased relatively more than yield, water productivity under aerobic cultivation increased by 20–40% (in one case even 80%) over that under flooded conditions. The groundwater table was very shallow, being above the soil surface under flooded conditions and on average 53 cm deep in the dry season and 28 cm in the wet season under aerobic conditions. Because of this shallow water table and frequent rainfall, the soil water content in the aerobic plots in the wet season was mostly between saturation and field capacity. A successful change from flooded to aerobic rice production requires the breeding of special aerobic rice varieties and the development of appropriate water and crop management practices.

Irrigated agriculture is by far the biggest user of freshwater, accounting for more than 70% of water withdrawals worldwide (Rosegrant 1998). In Asia, more than 50% of all water used for irrigation is used to irrigate rice (Barker et al 1999). The irrigated rice ecosystem covers about 79 million ha, which is about half of the world's total of 147 million ha under rice production. Irrigated rice in Asia produces about 75% of the worldwide rice production of 530 million tons (IRRI 1997). In Asia, rice is the most important staple, providing 35–80% of total calorie uptake. Thus, the present and future food security of Asia depend largely on the irrigated rice production system. This ecosystem, however, is increasingly threatened by water shortage. The reasons are diverse and location-specific, but include decreasing quality (chemical pollution, salinization), decreasing resources (e.g., falling groundwater tables, silting of reservoirs), and increased competition from other sectors such as urban and industrial users (Gleick 1993, Guerra et al 1998, Postel 1997). Therefore, there is a need to decrease water use in rice production and increase its use efficiency.

Water use in irrigated rice is high because the crop is grown under "lowland" conditions: the soil is puddled (wet-land preparation to create a muddy layer) and, after the transplanting of rice seedlings, the field is kept flooded with 3–5-cm depth of water until some 10 days before harvest. Because of the continuous presence of ponded water, there are large losses of water by evaporation from the water surface and by seepage and percolation out of the root zone. Moreover, the puddling of rice fields requires an extra amount of water when compared with that of other grain crops such as maize or wheat. Several water-saving technologies in lowland rice systems are being developed, such as alternate wetting and drying, direct wet seeding, and dry seeding (for an overview, see Bouman and Tuong 2001, Tabbal et al 2002).

A fundamentally different approach is to grow rice like an upland crop, such as wheat, on nonflooded aerobic soils. This way of growing rice saves water by (1) eliminating continuous seepage and percolation, (2) reducing evaporation, and (3) eliminating wet-land preparation. Traditional upland rice varieties are grown this way, but these have been selected to give stable yields in adverse environments with minimal external inputs. Alternatively, high-yielding lowland rice grown under aerobic conditions has been shown to save water, but at a severe yield penalty (De Datta et al 1973). Achieving high yields under irrigated aerobic conditions requires new varieties of "aerobic rice" (Bouman 2001). Evidence for the feasibility of aerobic rice comes from Brazil and northern China. In China, breeders have produced aerobic rice varieties with an estimated yield potential of 6 t ha^{-1}, which are now being grown on some 190,000 ha on the North China Plain (Bouman et al 2002, Wang Huaqi et al, this volume, Yang Xiaoguang et al, this volume). In Brazil, aerobic rice cultivars have come out of a 20-year breeding program with yields of 5–7 t ha^{-1} under sprinkler irrigation in farmers' fields (Silveira Pinheiro and Maia de Castro, personal communication). However, in both Brazil and China, it has been reported that high initial yields are difficult to sustain and that yields may decline severely after 3–4 years of continuous cropping. A possible cause for this yield decline is the buildup of soil-borne diseases such as nematodes (Prot et al 1994, Prot and Matias 1995).

In 2001, IRRI started activities to develop aerobic rice for the Asian tropics (IRRI 2001). Besides a breeding program to develop tropical aerobic rice varieties, optimal management practices have to be formulated for aerobic rice cultivation. This paper reports the first-year results of a field experiment on aerobic rice that aimed at (1) characterization of the hydrology, (2) quantification of water use, yield, and water-use efficiency of several promising cultivars, and (3) establishment of a benchmark to study the yield stability of rice under continuous aerobic cultivation.

This paper reports the first-year results, with emphasis on the hydrological characterization.

Materials and methods

Experiment layout

The field experiment was conducted in block K6/7 at the lowland farm of the International Rice Research Institute (IRRI), Los Baños, Laguna, Philippines (14°30′N, 121°1′E). The soil type was a typic Tropaqualf clay with 59% clay, 32% silt, and 9% sand, a total C content of 19.8 g kg^{-1}, and pH 6.7 (Bucher 2001). The experiment covered the dry season (DS), lasting from December to May, with an average rainfall of about 130 mm, and the wet season (WS), lasting from June to November, with an average rainfall of about 1,100 mm (IRRI Climate Unit).

The experiment was laid out in a split-plot design with four replicates. Three water treatments were used as the main plot: (1) aerobic conditions in the DS and the WS (AA), (2) aerobic in the DS but flooded in the WS (AF), and (3) flooded in both the DS and WS (FF). Each main-treatment plot was divided into four subplots. In the subplots, three varieties were tested per season, of which one was replaced. The two varieties that were tested in both the DS and WS were Apo (formerly IR55423-01) and IR43. In the DS, one of the subplots was planted with B6144F and was replaced by the hybrid rice IR7386H in the WS. The flooded plots were puddled and kept continuously flooded after transplanting until 2 weeks before harvest (terminal drainage). The water depth was initially 2 cm and gradually increased to 10 cm at full crop development. The aerobic plots were dry-plowed and harrowed. The soil was soaked 1 day before transplanting and then flooded for about 1 week with a 2–3-cm water layer to ease the establishment of the crop. After that, flash irrigation was applied when the soil moisture tension at 15-cm depth reached 30 kPa. There was no standing water except for the day of irrigation and during severe rainfall. To hydrologically separate the plots and prevent lateral seepage of water from the flooded into the aerobic plots, a set of double drains 40 cm deep were dug in between all the main plots. These double drains were connected to a 60-cm-deep collector drain running through the center of the whole experimental field, which, in turn, drained into 2-m-deep tube drains of the IRRI farm. Seepage through the bunds into the collector drain was visually noticed during the DS and plastic sheets were installed in the bunds of all plots along the collector drain down to 40 cm to prevent this water movement.

Twenty-one and 22-day-old seedlings were transplanted on 26 January in the DS and on 20 June in the WS at 25 × 10-cm spacing with 3 plants per hill. In the DS, N was applied as 60 kg ha^{-1} basal before transplanting, 60 kg ha^{-1} 25 days after transplanting (DAT), and 60 kg ha^{-1} 55 DAT. In addition, 30 kg P ha^{-1}, 40 kg K ha^{-1}, and 5 kg Zn ha^{-1} were applied as basal, and 30 kg P ha^{-1} 25 DAT. In the WS, N was applied as 20 kg ha^{-1} basal, 20 kg ha^{-1} 25 DAT, and 30 kg ha^{-1} 40 DAT. In addition, 30 kg P ha^{-1}, 20 kg K ha^{-1}, and 5 kg Zn ha^{-1} were applied as basal. The plots were kept weed-free by using herbicides and manual weeding.

Measurements

Irrigation water was supplied to the center of each main plot through 6-inch PVC pipes that were connected to the station's underground pressurized irrigation system. The water spilled from the pipes into 90° boxed-weirs (V-notch type), after which it was equally distributed among the four subplots. The amount of water applied was monitored at each irrigation by measuring the depth *h* (cm) of water over the V-notch. The discharge *Q* was computed using the following equation by Hansen et al (1980):

$$Q = 0.0138 \times h^{2.5} \text{ (L s}^{-1}\text{)} \quad (1)$$

Steel 60-cm-long percolation rings were installed down to below the compacted layer of the puddled topsoil (about 40 cm deep) in the flooded plots of each replicate to measure daily percolation rates. The tops of the rings were covered with plastic sheets to prevent evaporation outflow. Gauged tensiometers were installed at 15- and 35-cm depth in two subplots of each aerobic field for daily measurement of the soil moisture tension. For the daily measurement of the groundwater table, perforated PVC pipes were installed down to 1.75-m depth in the center of the bunds separating each main field. Drainage outflow from the whole experimental field was measured using a Parshall flume installed at the end of the central collector drain. Daily rainfall and pan evaporation (E_{pan}) data were collected from IRRI's on-site weather station.

Grain yield was determined from two 5-m^2 areas in the center of each subplot and is expressed at 14% moisture. In the WS, rats severely damaged the middle of some subplots (mainly the hybrid rice variety) and the sample areas in these damaged plots were chosen to avoid the damaged area as much as possible.

Calculations

The total water input was calculated for the period of land preparation and for the period of crop growth (from transplanting to harvest) for all plots by summing the water input by all rainfall and irrigation application events. For the flooded plots, the components of the soil water balance were calculated for the crop growth period:

$$I + R = ET + P + S + D + \delta W \text{ (mm)} \quad (2)$$

where I = irrigation, R = rainfall, ET = evapotranspiration, P = percolation, S = seepage, D = drainage, and δW = change in soil water storage. It was assumed that δW was negligible since the soil was saturated before and after the crop growth period. The I, R, and D terms were measured directly. The evapotranspiration, ET, was calculated from the pan evaporation, E_{pan}, using the equation derived for flooded rice at the IRRI farm by Wopereis et al (1994):

$$ET = 1.44\, E_{pan} \quad \text{mm d}^{-1} \quad (3)$$

In this calculation, ET equals potential ET since there are no limitations to transpiration by the crop. The cumulative percolation, P, was calculated as the difference in standing-water depth in the percolation rings between two days, summed over the crop growth period. The seepage term, S, was calculated as the closing term of equation 2. Daily S and P rates were zero in the last 2 weeks after terminal drainage.

In the aerobic plots, the outflow components of the water balance could not be calculated separately. Though seepage could safely be assumed to be negligible, the deep percolation and the evapotranspiration could not be estimated. Equation 3 is not applicable since it must be assumed that the aerobic conditions limited transpiration by the crop.

Water productivity, WP, was calculated as the weight of grain per unit of irrigation plus rainwater received during crop growth (g grain kg^{-1} water).

Results

Soil water balance

Table 1 gives the components of the soil water balance. The drainage outflow was below the detection level of the Parshall flume and therefore considered zero. For the flooded plots, the total water input during the crop growth period was about the same in the DS as in the WS. However, in the DS, 84% of the total water input was by

Table 1. Total water inputs and, for the flooded plots, the components of the water balance in the dry season (DS) and wet season (WS) of 2001, IRRI. In the DS, the flooded data are means of the FF treatment and the aerobic data are means of the AA and AF treatments. In the WS, the flooded data are means of the FF and AF treatments and the aerobic data are means of the AA treatment.

Farming activity	Irrigation (mm)	Rainfall (mm)	Total water input (mm)	Evapotranspiration (mm)	Percolation (mm)	Seepage (mm)
Flooded DS						
Land preparation	nm[a]	2	2	nm	nm	nm
Crop growth period	1,148	222	1,370	547	128	695
Flooded WS						
Land preparation	358	76	434	nm	Nm	nm
Crop growth period	574	751	1,325	554	62	709
Aerobic DS						
Land preparation	nm	2	2			
Crop growth period	431	222	653			
Aerobic WS						
Land preparation	53	76	129			
Crop growth period	79	751	830			

[a]nm = not measured.

irrigation, whereas in the WS this was only 43%. Total evapotranspiration, percolation, and seepage flows were also similar in the DS and the WS. The mean percolation rate of the flooded plots was 1.6 mm d^{-1} (±0.3 standard deviation) in the DS and 0.7 mm d^{-1} (±0.2 standard deviation) in the WS. The daily combined seepage and percolation rate (S&P) from the flooded plots, calculated from transplanting to the start of terminal drainage, was 10.3 mm d^{-1} in the DS and 8.8 mm d^{-1} in the WS. These values are in the lower range of the 4–36.2 mm d^{-1} found by Wopereis et al (1994) under different conditions in a comparable field at the IRRI farm, and in the middle of the range of 0–25.8 mm d^{-1} reported for farmers' fields in three provinces in Luzon, Philippines, by Wickham and Singh (1978). For heavy clay soils, Bouman (2001) reported common values of 1–5 mm d^{-1}. The S&P rate was slightly lower in the WS than in the DS because of the installed plastic sheets. Also, the bunds were more cracked in the DS than in the WS because of drier weather conditions that promoted the drying of the outside of the bunds.

Water use and irrigation

The total water use in the aerobic plots was much lower than in the flooded plots (Table 1). In the crop growth period, total water use in the aerobic plots was only 48% of that in the flooded plots in the DS and 63% of that in the WS. For irrigation water input, the differences were even more pronounced: irrigation water input in the aerobic plots was only 38% of that in the flooded plots in the DS and 14% of that in the WS. The amount of water required for land preparation was not observed in the DS. In the WS, however, the wet-land preparation used in soaking and puddling of the flooded plots required a considerable amount of irrigation water (358 mm). The total amount of water input for flooded rice from the start of land preparation to harvest was therefore 1,759 mm. This compares well with values found by Tabbal et al (2002) in farmers' fields in central Luzon. In aerobic plots, water was required only during land preparation to briefly soak the land to ease transplanting. Only 53 mm of irrigation water was used, and the total water input from land preparation to harvest was 959 mm.

Figure 1 gives the timing of irrigation water application and of rainfall events. In the flooded plots, the irrigation interval was about 3–4 days in both the DS and the WS, and some 25 irrigation applications were given in the crop growth period in the DS and 21 in the WS. However, the mean application depth was higher in the DS (48 mm) than in the WS (28 mm) because rainfall in the WS provided much of the required water input. In the crop growth period of the DS, irrigation was applied eight times with an average depth of 54 mm and an interval of 7–8 days. In the WS, irrigation water was applied twice before transplanting (53 and 36 mm) and only once during crop growth (43 mm) before fertilizer application. No further irrigation water was applied during the rest of the crop growth period because of abundant rainfall.

Groundwater table and soil moisture tension

Figure 2 illustrates the dynamics in groundwater depth. The groundwater table was close to the ponded water level in the flooded rice plots, and was on average 8.3 cm

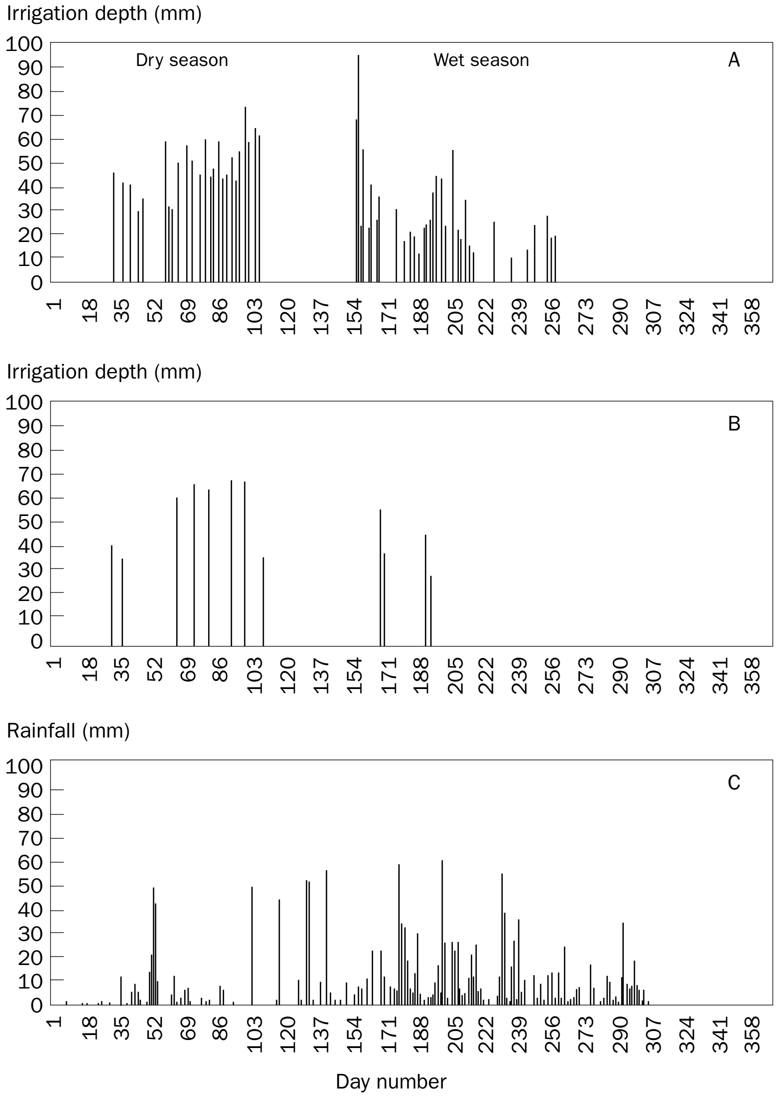

Fig. 1. Amount and frequency of irrigation water application in flooded (A) and aerobic (B) fields and of rainfall (C), 2001. In A, the dry-season (DS) data are means of the FF treatment and the wet-season (WS) data are means of the FF and AF treatments. In B, the DS data are means of the AA and AF treatments and the WS data are means of the AF treatment.

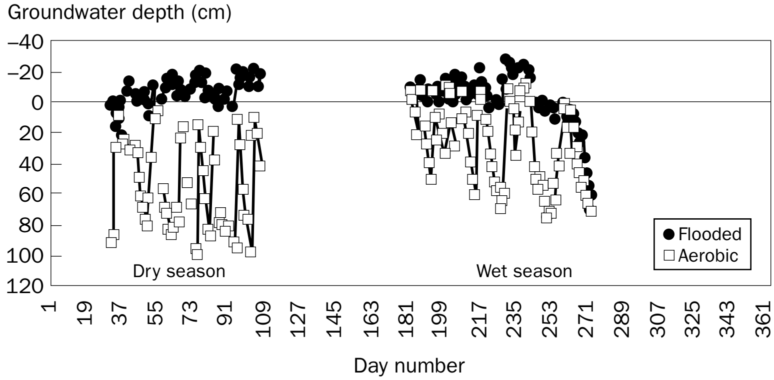

Fig. 2. Average depth of groundwater table under aerobic and flooded rice plots, 2001. In the dry season (DS), the flooded data are means of the FF treatment and the aerobic data are means of the AA and AF treatments. In the wet season (WS), the flooded data are means of the FF and AF treatments and the aerobic data are means of the AA treatment.

above the soil surface in the DS and 1.4 cm above the soil surface in the WS. In the WS, the groundwater table subsided to 70-cm depth after terminal drainage. The low internal drainage of the heavy clay was the cause for the continuous shallowness of the groundwater table. The drains along the aerobic plots brought the groundwater table under the aerobic plots down from close to the surface after an irrigation or rainfall event to 80–100-cm depth in the DS and to 60–80-cm depth in the WS, within a couple of days. The average depth of the groundwater table was 53 cm in the DS and 28 cm in the WS. The average depth was lower in the WS than in the DS because of the frequent rainfall that recharged the groundwater.

Figure 3 illustrates the dynamics in soil water tension in the aerobic plots. In the DS, the soil moisture tensions at 15-cm depth varied mostly from 0 to 30 kPa, as intended with the planned irrigation scenario. In the WS, however, the heavy and frequent rainfall kept the soil very wet and tensions at 15-cm depth exceeded 5 kPa only in six cases (days) before terminal drainage. In the DS, the soil water tension was much lower at 35-cm depth than at 15-cm depth. There are three explanations for the soil being drier at shallower depths than at deeper depths: (1) most of the roots were concentrated in the top of the soil profile and extracted water for transpiration, (2) evaporation from the soil surface extracted water from the topsoil, and (3) the deeper soil layers were kept relatively wet by the shallow groundwater table. In the WS, the differences between soil water tension at 15- and at 35-cm depth were small because of the frequent rainfall and the shallow groundwater table.

Yield and water productivity

Table 2 presents yields. In the DS, all plots were infected by stem borer (visual estimate of 5–10% whiteheads) and variety B6144F lodged completely under both flooded and aerobic conditions. Mole crickets damaged some plants in aerobic plots in the regreening stage, but the dead plants were replaced with new plants. In the WS, the

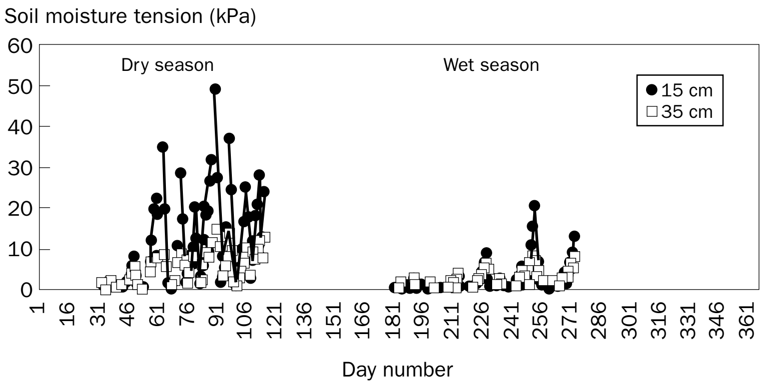

Fig. 3. Average soil moisture tension at 15- and 35-cm depth in aerobic rice plots, 2001. In the dry season (DS), the data are means of the AA and AF treatments and, in the wet season (WS), the data are means of the AA treatment.

Table 2. Yield (t ha^{-1}) of rice varieties cultivated under aerobic and flooded conditions, dry season (DS) and wet season (WS), 2001, IRRI.

Season:		DS		WS	
Variety	Treatment	Soil condition	Yield	Soil condition	Yield
Apo	AA[a]	Aerobic	4.37 (0.17)[b]	Aerobic	4.19 (0.21)[b]
	AF	Aerobic	4.35 (0.42)	Flooded	5.07 (0.30)
	FF	Flooded	5.06 (0.24)	Flooded	5.30 (0.20)
IR43	AA	Aerobic	3.41 (0.46)	Aerobic	4.10 (0.26)
	AF	Aerobic	3.70 (0.43)	Flooded	4.74 (0.65)
	FF	Flooded	5.90 (0.53)	Flooded	4.81 (0.28)
B6144F	AA	Aerobic	2.37 (0.36)	Aerobic	na[c]
	AF	Aerobic	2.73 (0.40)	Flooded	na
	FF	Flooded	3.85 (0.73)	Flooded	na
IR73868H	AA	Aerobic	na	Aerobic	3.88 (0.94)
	AF	Aerobic	na	Flooded	5.59 (0.25)
	FF	Flooded	na	Flooded	4.85 (0.30)

[a]A = aerobic, F = flooded; first position indicates the DS and second position the WS. [b]Values in parentheses are standard deviation. [c]na = not applicable.

aerobic plots of the hybrid IR73868H were heavily damaged by rats during flowering, which led to a reduction in yield. In both the DS and the WS, considerable weed growth occurred in some plots, which was controlled by manual weeding.

Yields in the DS were relatively low when compared with typical DS yields of high-yielding lowland varieties under flooded conditions. For comparison, at the IRRI farm, yields of IR72 under flooded conditions reached 7.8 t ha^{-1} in the DS of 2001 (IRRI, unpublished data). In the WS, yields in our experiment were closer to typical lowland rice yields under flooded conditions; IR72 yields in flooded fields at the IRRI farm reached 5.7 t ha^{-1} in 2001 (IRRI, unpublished data). All four varieties

Table 3. Water productivity (WP; g grain kg^{-1} water) of rice varieties cultivated under aerobic and flooded conditions, dry season (DS) and wet season (WS), 2001, IRRI.

Season:		DS		WS	
Variety	Treatment	Soil condition	Yield	Soil condition	Yield
Apo	AA[a]	Aerobic	0.67	Aerobic	0.50
	AF	Aerobic	0.67	Flooded	0.38
	FF	Flooded	0.37	Flooded	0.40
IR43	AA	Aerobic	0.52	Aerobic	0.49
	AF	Aerobic	0.57	Flooded	0.36
	FF	Flooded	0.43	Flooded	0.36
B6144F	AA	Aerobic	0.36	Aerobic	na
	AF	Aerobic	0.42	Flooded	na
	FF	Flooded	0.28	Flooded	na
IR73868H	AA	Aerobic	na[b]	Aerobic	0.47
	AF	Aerobic	na	Flooded	0.42
	FF	Flooded	na	Flooded	0.37

[a]A = aerobic, F = flooded; first position indicates the DS and second position the WS.
[b]na = not applicable.

yielded less under aerobic conditions than under flooded conditions. Compared with those of the flooded plots, the yield reductions in aerobic plots were 14%, 40%, and 34% in the DS for Apo, IR43, and B6144F, respectively, and 19%, 14%, and 26% in the WS for Apo, IR43, and IR73868H, respectively. The yield reductions were consistently smallest in Apo, which may indicate that Apo is better adapted to aerobic conditions than the other varieties. However, the yield reductions of B6144F and IR73868H may have been aggravated by lodging and rat damage, respectively.

Table 3 gives the water productivities. For flooded rice, these values are in the lower range of the values of 0.3–1.1 g kg^{-1} reported for farmers' fields in the Philippines by Bouman and Tuong (2001). Under aerobic conditions, water productivity was 19–39% higher than under flooded conditions, whereas this increase was even 81% for Apo in the DS.

Conclusions and discussion

Many "start-up problems" were encountered in the first year of testing the aerobic cultivation of rice, for example, weeds, mole crickets, and rats particularly infested the aerobic plots compared with the flooded plots. We expect to learn how to manage these problems better in the second year and aim at raising yields. Particular care should be taken before bringing the aerobic rice technology to farmers to look at integrated crop management and protection. The field conditions of our experimental site were relatively wet because of the shallow groundwater table and the high clay content of the soil that limits internal drainage. To obtain more evidence for the water-saving potential of aerobic rice, we suggest testing this system under different ("drier") soil and hydrological conditions.

The varieties used in this study are upland varieties and hybrid rice that performed relatively well under upland conditions (George et al 2001, 2002). These varieties, however, were not especially bred for irrigated aerobic soil conditions under high nutrient inputs as we used in our study. Upland varieties have generally been selected to give stable yields in adverse environments with minimal external inputs. They are mostly tall and unresponsive to inputs and, under favorable conditions, have a low harvest index and tend to lodge (Lanceras et al 2002), such as happened with B6144F in our study. Varieties for aerobic rice cultivation should therefore have lodging resistance, an ability to partition a greater proportion of plant matter into grain, and higher nutrient responsiveness.

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Crop-water responses of aerobically grown rice: preliminary results of pot experiments

J. Nieuwenhuis, B.A.M. Bouman, and A. Castañeda

Aerobic rice is a new technology to reduce water input in rice production. Two pot experiments were carried out at IRRI in 2001 to study the physiological water use (transpiration), growth, and yield formation of high-yielding upland rice grown under irrigated aerobic conditions. The treatments consisted of different combinations of flooded and aerobic conditions in the vegetative, reproductive, and grain-filling stages using two varieties and two soil types. Three levels of aerobic conditions were used: minimum allowed soil water potentials of –10, –30, and –70 kPa. In general, the highest yields were obtained under continuously flooded conditions. The introduction of aerobic phases reduced physiological water use, biomass, and yield. Under continuously aerobic conditions, yield reductions were 34–74%. There was no relationship between the magnitude of yield reduction and soil water potential reached in the aerobic phase. The reduction in yield can be minimized, and water productivity maximized, by “smart” water management. Yield reductions in clay soil were only 2–6% under aerobic conditions with flooding in the reproductive phase and 8–12% under continuous flooding with aerobic conditions in the reproductive phase. In the clay-loam soil, the yields under such aerobic-flooded combinations were even higher than under continuous flooding. Water productivity was highest under aerobic conditions with flooding during the reproductive phase (values up to 0.96–1.24 g L^{-1}, with no demonstrated effect of level of soil water potential). The second highest water productivities were obtained under continuous flooding with aerobic conditions during the reproductive stage, with values of 0.81–0.95 g L^{-1}.

Rice is the staple food in Asia (IRRI 1997). It is also one of the most water-consuming crops in the world (Guerra et al 1998). As water for agriculture is becoming increasingly scarce, there is pressure to find ways to reduce water use and increase water-use efficiency in rice production, while maintaining high yields. Conventional lowland rice fields have considerable so-called "nonproductive" water losses by percolation, seepage, and evaporation. It has been estimated that seepage and percolation account for 50–80% of the total water outflow from the field (Sharma 1989). Estimating that evaporation makes up about 30% of combined evapotranspiration, then only some 13–33% of total water outflow is consumptive or "physiological" water use by transpiration. Thus, many technologies to save water focus on the reduction of the nonproductive water losses (Bouman, 2001, Tabbal et al 2002). A new water-saving technology is to grow rice aerobically, that is, in nonpuddled and nonflooded soil with irrigation (Bouman 2001). Evidence for the feasibility of "aerobic rice" comes from North China, where breeders have developed temperate aerobic rice varieties that combine a high yield potential with a low water requirement (Wang Huaqi et al and Yang Xiaoguang et al, this volume). The International Rice Research Institute (IRRI) has taken up the challenge to develop tropical aerobic rice systems. One of the research questions is how the rice crop reacts to aerobic soil conditions in terms of physiological water use, growth, and yield formation. Nonsaturated soil conditions in rice are known to adversely affect crop growth by reducing leaf expansion, tillering, and photosynthesis, and by accelerating leaf senescence and increasing spikelet sterility (Ekanayake et al 1989, Hirasawa 1999, Bouman and Tuong 2001). However, no research has yet been done to investigate crop-water responses of aerobic rice. In this paper, we present the results of pot experiments aimed at quantifying the physiological water use and responses of rice grown under full or partly aerobic conditions. Since no tropical aerobic rice varieties exist yet, the experiments used existing high-yielding upland varieties.

Materials and methods

Two pot experiments were conducted in the dry and wet season of 2001 at IRRI, Los Baños, Philippines. The dry-season (DS) experiment was conducted in a screenhouse and the wet-season (WS) experiment in a glasshouse. The following treatments were implemented:

DS. Two tropical upland rice varieties were used: IR43 (an improved and widely grown upland variety released some years ago) and Apo (also known as IR55423-01 and just released in the Philippines in 2001). The soil type was a typic Tropaqualf clay collected from the IRRI lowland farm (59% clay, 32% silt, and 9% sand; Bucher 2001). The treatments consisted of different combinations of either flooded (F) or aerobic (A) conditions in the vegetative (from transplanting to panicle initiation), reproductive (from panicle initiation to end of flowering/start of grain filling), or grain-filling (end of flowering to maturity) stages of crop growth. In Apo, seven combinations were implemented and in IR43 three (see Table 1). The treatments are indicated by a three-letter code in which each letter indicates the water condition (F or A)

Table 1. Yield, yield components, transpiration, and water productivity of the dry-season experiment.

Variety	Treatment	Yield (g pot^{-1})	Biomass (g pot^{-1})	Panicles per pot	Grains per panicle	1,000-grain weight (mg)	Sterility (%)	Transpiration (L pot^{-1})	Water productivity (g L^{-1})
Apo	FFF	27.8	57.2	12.5	151	19.6	24.8	25.7	1.08
	AAA	20.0	43.7	9.5	127	19.3	13.4	18.3	1.10
	AFA	26.1	54.1	9.5	154	20.4	12.4	21.0	1.24
	AFF	25.0	51.3	9.5	155	18.9	9.2	22.1	1.13
	FAF	24.3	55.4	11.0	134	20.8	21.0	25.4	0.95
	AAF	19.7	45.0	8.0	136	19.6	8.6	17.8	1.08
	FAA	23.0	47.1	11.0	117	20.1	11.7	21.8	1.05
LSD[a]		6.3	11.4	1.4	ns	1.7	14.6	4.1	0.21
IR43	FFF	26.6	64.9	16.8	90	24.2	24	26.4	1.01
	AAA	23.5	52.6	13.0	94	25.0	16	20.6	1.14
	AFA	26.3	59.7	12.8	111	25.1	22	24.3	1.09
LSD		ns	ns	ns	ns	ns	ns	ns	ns

[a]LSD = least significant difference at the 5% level. ns = not significant.

and the letter's position in the code indicates the period of implementation (first position indicates vegetative phase, second position indicates the reproductive stage, third position indicates the grain-filling stage). For example, AFA means aerobic conditions in the vegetative stage, flooded in the reproductive stage, and aerobic in the grain-filling stage. In the flooded phase, a 2–5-cm layer of standing water was maintained. In the aerobic phase, the soil was allowed to dry out until field capacity (defined as –10 kPa soil water potential), after which the soil was brought to saturation again. In the transition from the flooded to aerobic phase, the pots were drained at the bottom for 24 h. In all pots, fertilizers were applied at a rate assumed to be nonlimiting to crop growth: 180 kg N ha^{-1} (in the form of urea, in three splits), 60 kg P ha^{-1} (as P_2O_5, in two splits), 40 kg K ha^{-1} (as K_2O, basal), and 5 kg Zn ha^{-1} (as $ZnSO_4$, basal). Crop samples at harvest confirmed that nutrients were nonlimiting in all treatments (data not shown).

WS. Only variety Apo was used. Two soil types were used: the same typic Tropaqualf clay from the lowland farm and an isohypothermic, mixed typic Tropudalf loamy clay collected from IRRI's upland farm (39% clay, 43% silt, and 18% sand; Wopereis 1993). In both soils, six treatments were imposed that were (as in the dry season) defined by either flooded or aerobic conditions in the three growth stages. Two aerobic conditions were implemented: in A-30, the soil was allowed to dry out to –30 kPa before irrigation; in A-70, the soil was allowed to dry out to –70 kPa. The treatment combinations are given in Table 2. Fertilizers were applied in the same form as in the DS as 100 kg N ha^{-1} (three splits), 30 kg P ha^{-1} (basal), 40 kg K ha^{-1} (basal), and 5 kg Zn ha^{-1} (basal).

Three seedlings of 21 d were transplanted into 25-cm high pots with a diameter of 20 cm. The pots were filled with about 5 kg of pulverized dry soil that was brought to saturation to ease transplanting. The treatments started 14 and 12 d after transplanting in the DS and WS, respectively. Before that, the soil was kept flooded with a shallow (2 cm) water layer. All pots were covered after transplanting by a plastic sheet to avoid water loss by evaporation. The pots were placed in units of 5×20 pots for each treatment with a single-pot border row. Each pot took up a space of 400 cm^2. The treatments were laid out in a randomized complete block design with two replicates.

Tensiometers were placed in two pots of each treatment unit with the porous cup at 10-cm depth in the center of the pot. Every morning, soil water tension was recorded and each pot was weighed before and after irrigation. Irrigation water was applied as necessary based on the tensiometer readings or the depth of standing water. At maturity, four pots were harvested to measure total biomass, yield, and yield components. Grain yield was standardized to 14% moisture content. Crop transpiration was calculated from the differences in daily pot weights. Water productivity was calculated as grain yield divided by the total amount of water transpired since transplanting. The statistical software package SAS was used to calculate the least significant difference (LSD) between treatments.

Table 2. Yield, yield components, transpiration, and water productivity of the wet-season experiment.

Variety	Treatment	Yield (g pot^{-1})	Biomass (g pot^{-1})	Panicles per pot	Grains per panicle	1,000-grain weight (mg)	Sterility (%)	Transpiration (L pot^{-1})	Water productivity (g L^{-1})
Clay	FFF	22.5	67.1	12	116	21.2	20	26.06	0.86
	AAA-30	9.7	46.4	14	90	16.6	54	13.05	0.77
	AAA-70	9.8	43.6	11	96	17.1	46	13.27	0.74
	AFA-70	21.6	57.3	10	119	22.5	15	18.72	1.15
	AFA-30	21.1	57.6	9	147	20.8	20	20.10	1.05
	FAF-70	20.6	74.5	19	101	20.7	47	22.46	0.91
Clay-loam	FFF	19.4	62.6	11	109	20.6	24	27.47	0.71
	AAA-30	16.8	77.7	23	107	18.3	62	23.14	0.73
	AAA-70	6.5	61.3	27	81	14.1	79	21.57	0.30
	AFA-70	25.4	79.5	14	121	21.0	22	26.66	0.97
	AFA-30	23.4	81.2	12	132	22.9	32	24.38	0.96
	FAF-70	23.0	80.3	24	102	19.6	49	28.50	0.81
LSD[a]		7.5	13.8	4.3	40	2.97	19	4.19	0.46

[a]LSD = least significant difference at the 5% level.

Results

Dry season

Production. Results of the DS experiment are given in Table 1. For Apo, the yield of the continuously flooded treatment FFF was highest, followed immediately by that of the AFA treatment (only a 6–10% yield reduction). The treatment with aerobic conditions in the reproductive stage and flooding in the vegetative and grain-filling stages (FAF) was third with a yield reduction of 13%. The two treatments that were aerobic in the vegetative and reproductive stages (AAF and AAA) had the lowest yield, with a reduction of about 29% compared with that of the continuously flooded treatment. Only the yields of these two treatments were significantly different from the others (which were not significantly different from each other). The flooding in the grain-filling stage (AAF) did not result in a yield increase over keeping the soil continuously aerobic (AAA). For IR43, the patterns were similar, but the differences between the treatments were smaller. The continuously aerobic treatment had a yield reduction of only 12% compared with that of the continuously flooded treatment. Total biomass production showed more or less a similar pattern as that for yield, for both varieties.

Yield components. For Apo, the number of panicles per pot was significantly lower in all treatments that were aerobic in the vegetative stage (A**) than in the treatments that were flooded in that stage. Out of the A** treatments, the two with flooding in the reproductive stage had a higher number of grains per panicle than the others (although not significant), which may explain in part their higher yields. The thousand-grain weight barely showed significant differences among the treatments. Contrary to expectations, the highest spikelet sterility was observed in the continuously flooded treatment (remains unexplained so far). For IR43, the differences in the yield factors were statistically not significant among treatments. As in Apo, the highest spikelet sterility in the continuously flooded treatment is noteworthy.

Water use and water productivity. For Apo, the total amount of water transpired was highest in the continuously flooded treatment and in the flooded treatment with an aerobic phase in the reproductive stage only (FAF). The lowest water use was observed in the AAA and AAF treatments, which transpired about 30% less than the continuously flooded treatment. Combining a relatively high yield with an intermediate amount of water use, the AFA treatment had the highest water productivity of all treatments. Its opposite, the FAF treatment, combined a medium yield with a high water use and had the lowest water productivity. The differences between these two treatments were statistically significant. For IR43, the differences in water use and water productivity were statistically not significant.

Wet season

Production. Results of the WS experiment are given in Table 2. The maximum yields obtained in the WS (22.5–25.4 g pot^{-1}) were only some 13% lower than those obtained in the DS (26.6–27.8 g pot^{-1}). For the clay soil, the highest biomass was obtained in the two treatments with the longest periods of flooding (FAF and FFF). The two aerobic treatments with flooding in the reproductive stage (AFA) had similar biomass values that were 14% lower than that of the continuously flooded treatment. The two continuously aerobic treatments (AAA) also had similar biomass values that were about 32% lower than that of the continuously flooded treatment. Yield was highest in the continuously flooded treatment. The two aerobic treatments with flooding in the reproductive stage (AFA) had about the same yields, which were only 5% lower than that of the continuously flooded treatment. The two continuously aerobic treatments (AAA) had the same yields, which were a dramatic 56% lower than that of the continuously flooded treatment. This reduction in yield was relatively more severe than the reduction in total biomass. The yield and biomass productions in the partly aerobic treatments were not affected by the soil water potentials reached (–30 or –70 kPa). The single FAF treatment performed well, with the highest total biomass recorded and a high yield.

The crop performed generally better in the clay-loam soil than in the clay soil. On average, the biomass and yield were 28% and 9% higher, respectively, in clay-loam soil than in clay soil. The differences in biomass and yield between treatments, however, were less clear than in the clay soil. The continuously flooded treatment had a relatively poor performance: the biomass production was nearly the lowest (only AAA-70 was lower) and the yield ranked only fourth. The two aerobic treatments with flooding in the reproductive phase (AFA) and the single FAF treatment had the highest biomass production and yield, which were not significantly different from each other. The biomass of the continuously aerobic treatments at –30 kPa and –70 kPa was 4% and 25% lower, respectively, than the highest value. The yield of the continuously aerobic treatments was 34% lower than the highest value at –30 kPa and a dramatic 74% lower at –70 kPa.

Yield components. The most consistent difference occurred between the continuously aerobic treatments on the one hand and all other treatments on the other, in both soil types. In both the AAA treatments, the number of grains per panicle and the thousand-grain weight were consistently and mostly significantly lower, and the percentage spikelet sterility higher, than in all other treatments. This explains the much lower yields (34–74% reduction compared with the highest value) in these two treatments compared with their relative reduction in biomass (4–32% reduction compared with the highest value). The single FAF treatment also had relatively low numbers of grains per panicle and high sterility rates, but its yield was still relatively high because it had a high total biomass production. In the clay-loam soil, the number of panicles was relatively high in the continuously aerobic treatments and in the FAF treatment. This was caused by the production of second-generation tillers at grain filling, which did not occur in the clay soil.

Water use and water productivity. The trends in water use were clearest and significantly different in the clay soil. The continuously flooded treatment had the highest water use, followed by the FAF treatment. The two AFA treatments had intermediate levels of water use, whereas the continuously aerobic treatments had the lowest, with only 50% of that of the continuously flooded treatment. Because of the combination of relatively high yields with medium levels of water use, the AFA treatments had the highest water productivities. The FAF treatment had a second-best water productivity. Despite their low water use, the continuously aerobic treatments had the lowest water productivity because of their very low yields. Though the differences in water use were less pronounced in the clay-loam soil, the trends were similar to those in the clay soil.

Concluding remarks

Except for the clay-loam soil in the WS, the highest biomass production and yield were obtained under continuous flooding. The introduction of aerobic conditions in one of the three stages of crop growth (vegetative, reproductive, or grain filling) reduced the physiological water use (transpiration), but also reduced biomass and yield, even when the soil water potential was kept between saturation and field capacity (0 to –10 kPa). Under continuously aerobic conditions, yield reductions compared with flooded rice were 34–74%. There was no relationship between magnitude of yield reduction and soil water potential reached in the aerobic phase. However, the reduction in biomass and yield can be minimized by "smart" water management. With all three threshold levels of soil water potential during the aerobic phase (–10, –30, and –70 kPa), yield reductions in the clay soil were only about 2–6% under aerobic conditions with flooding in the reproductive stage and 8–12% under continuous flooding with aerobic conditions in the reproductive stage. In the clay-loam soil, yield under such combinations of aerobic-flooded conditions was even higher than under continuous flooding, but this may be an artifact caused by the poor performance of the flooded treatment (to be further investigated). Also, these combinations of aerobic-flooded conditions maximize water productivity while maintaining high yields. In field situations, the increase in water productivity of rice grown aerobically over rice grown under flooded conditions will be even higher since, in the field, the losses by seepage, percolation, and evaporation from the ponded water will also be reduced (e.g., Yang Xiaoguang et al, this volume).

In absolute terms, the yields and water productivities found in this study are relatively low compared with the values obtained with high-yielding lowland rice varieties under flooded conditions. Wopereis (1993) reported yields in continuously flooded treatments of 33 and 29 g pot^{-1} using IR20 and IR72, respectively, in a dry-season pot experiment at IRRI. Bouman and Tuong (2001) found in a comparative study that water productivity in covered pot experiments could reach up to 1.9 g L^{-1}. Values found in our experiment (high values of 0.96–1.24 g L^{-1} and low values of 0.3–0.7 g L^{-1}) are in an average range. Further breeding efforts have to concentrate on the development of true aerobic rice varieties that maintain a high spikelet fertility and number of grains per panicle under aerobic conditions.

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The ground-cover rice production system (GCRPS): a successful new approach to save water and increase nitrogen fertilizer efficiency?

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To evaluate a new production technique for rice, the so-called ground-cover rice production system (GCRPS), three field experiments were started in 2001 at three locations (Beijing, Nanjing, and Guangzhou) representing a wide range of environmental and agricultural conditions. Within these experiments, water balance (precipitation/irrigation, surface runoff, leaching, evaporation, and evapotranspiration), nitrogen balance (plant uptake, leaching, N_2O and NH_3 emissions), and greenhouse gas emissions (N_2O and CH_4) were determined. Preliminary data demonstrate that the GCRPS reduced water demand by up to 60% and increased water-use efficiency by 54% in Beijing. Yields under the GCRPS were 11–31% lower than in paddy rice. Lower soil water content during the tillering period and deficiency of nitrogen and microelements might be responsible for these lower yields (particularly in Beijing). Nitrogen fertilizer-use efficiency (isotope ^{15}N method and difference method) was lower in the GCRPS treatments than in the paddy rice system. However, pot experiments indicate a substantial improvement of 10–20% in the very low nitrogen-use efficiency of 20–40%, which is frequently reported for paddy rice.

Paddy rice production is the most important rice production system in China, both because the average yield of paddy rice is higher than that of maize and wheat (Editorial Board of China 2000) and because rice production is economically more remunerative for exports in the international market. Exports of rice from China increased dramatically over the past 10 years (China Agricultural Statistic Yearbook 1983-1999). However, agricultural water use in China accounts for 71% of the total water consumption and 70% of all water used in agriculture is consumed in paddy rice production. In the past decade, increasing agricultural production and industrial growth have led to a severe shortage of water resources. Particularly in the rice regions of northern China with a cultivated area of 4 million hectares, the problem has reached dramatic proportions (Wang and Zhou 2000). Mitigation strategies need to take into account that paddy rice production is the most important and most widespread rice production system in China. Paddy rice yields are high and grain quality generally favorable. At the same time, the water-use efficiency, in terms of grain production per unit of water use, of paddy rice is very low; therefore, the demand for irrigation is at least twice as high as for other cereals. Interestingly, the physiological demand of the rice crop for transpiration accounts for only 10–12% of total water use in paddy rice production, with 16–18% and 50–72% being lost in evaporation and seepage, respectively (Beng et al 1998, Wang and Zhou 2000). This is the main reason that the water-use efficiency of paddy rice is so much lower than that of other crops, for example, wheat. The low nitrogen fertilizer-use efficiency is also closely linked to the special conditions in the paddy soil.

In the late 1990s, a new rice cultivation technique, the so-called ground-cover rice production system (GCRPS), was suggested, in which lowland rice fields are irrigated before planting to 80–90% of water-holding capacity. Subsequently, the soil surface is covered by plastic film (0.014 mm) or plant mulch and the soil is kept at 70–90% of water-holding capacity, depending on crop development stage (Liang et al 1999, Wu et al 1999). An experiment financed by the German Research Council (DFG) and the National Natural Science Foundation of China (NSFC) began in 2001 at three locations (Beijing, Nanjing, and Guangzhou), representing a wide range of soil types, yearly temperature and precipitation, groundwater level, and production rotations. The aim of the present work is therefore to clarify whether the new technology for rice cultivation (GCRPS) could increase water- and nitrogen-use efficiency. To evaluate this rice production system, compared with the traditional paddy rice production system, water balance (precipitation, irrigation, surface runoff, percolation, evaporation, and evapotranspiration), nitrogen balance (plant uptake, leaching, N_2O emissions), and greenhouse gas emissions (N_2O and CH_4) were determined.

Materials and methods

Setup of field experiment

The three field experiments were located at the experiment stations in Beijing, Nanjing, and Guangzhou on different soil types: an Ustochrept with a soil texture of light loam at 0–35 cm and sandy loam at 35–65 cm in Beijing, a Halaquept in Nanjing, and a kandite Udult in Guangzhou. Average annual temperature and precipitation are 11.8 °C and 577 mm in Beijing, 15.3 °C and 1,034 mm in Nanjing, and 21.8 °C and 1,682 mm in Guangzhou, representing a wide range of environmental and agricultural conditions. The main experiment had six treatments, laid out according to a one-factorial block design, with three replications. The six treatments were T1—traditional paddy rice production system (paddy); T2—paddy rice cultivated under aerobic conditions, soil surface covered with plastic film (film); T3—surface covered with mulch (mulch); T4—surface not covered (bare); T5—upland rice variety cultivated under aerobic conditions (upl-bare); and T6—upland rice variety cultivated under aerobic conditions, surface covered with plastic film (upl-film). The last treatment was included only in Beijing.

The experiment consisted of a paddy area and an upland area. The paddy area comprised the Paddy Control treatment plots, as well as the Isolation Paddy plots. The upland area comprised the five GCRPS treatments and three Isolation Upland plots. The GCRPS treatments were randomized within each of the three replications in the upland area. All plots were enclosed by isolation dams of 50 cm width and 15 cm height to assure independent hydrological conditions. The layout of one replication of all plots is given in Figure 1. Additionally, in the Paddy Control treatment, a wooden pathway was installed to avoid soil vibration by walking. Within each of the treatment plots, the sampling areas were clarified for special measurements of soil and plant samples, harvest data, water balance, ^{15}N stable isotope fertilizer efficiency, and greenhouse gas emissions (Fig. 1).

The N_0 plots of the respective treatments were located within the protection zone, the boundary of the main experimental field. Each N_0 plot had a size of 3×3 m, of which the inner 0.9×1 m was finally harvested. The isotope plots were enclosed by metal frames of $200 \times 180 \times 40$ cm, driven into the soil to a depth of 25 cm.

Fertilization

Nitrogen fertilizer (225 kg N ha^{-1} as urea) was given in a single dressing at the start of the experiment in all GCRPS treatments. In the paddy area, nitrogen fertilizer was split into three doses: 40%, 30%, and 30% as basic fertilization and topdressing at the beginning of tillering and at the booting stage, respectively. Phosphorus and potassium were given at 90 kg P ha^{-1} and 90 kg K ha^{-1} in all treatments at the start of the experiment.

Water balance

Establishment of an exact water balance was one of the major aims of the experiment. This balance is based on accurate measurements of all inputs (irrigation and precipi-

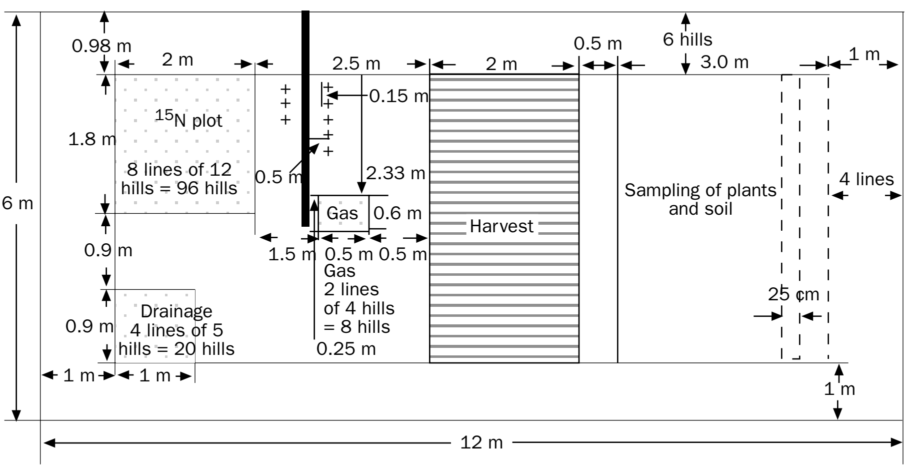

Fig. 1. Layout of one plot and location of subplots for protected final harvest, drainage, ^{15}N plots, intermediate sampling of plant and soil, and trace gas measurements.

tation) and outputs (evaporation and drainage). In each plot, a water meter was installed to measure inputs in irrigation water. Precipitation was measured with an automatic precipitation collector 150 m from the experiment field. Free water evaporation was estimated from open metal boxes (1 × 0.9 m, 0.3-m depth) installed in the Isolation Paddy plots. Actual evaporation in the Paddy Control plots with a growing rice crop was monitored in parallel through a similar box in each plot (0.2 × 1.5 m, 30-cm depth). Evaporation in the GCRPS treatment was recorded during five to eight measuring campaigns using micro-lysimeters for the treatments bare soil and straw cover (Boast and Robertson 1982).

Sampling and analysis

Every 2 weeks, starting 4 weeks after sowing or transplanting, plant samples from 0.3 m^2 of soil surface (0.5 × 0.6 m = 8 hills) and soil samples were taken. Soil samples were collected immediately following plant sampling at the same place. Number of plants, number of tillers, plant fresh weight, plant dry weight, N content, leaf area index, and soil N_{min} content were determined. In the ^{15}N subplots, at five relevant growth stages, three plants per plot were harvested. At final harvest, only the central 0.9 m^2 of each ^{15}N plot was harvested and fresh weight determined. The complete samples from these 0.9-m^2 areas were dried, weighed again, and chopped into 3-cm pieces and representative subsamples were ground and their ^{15}N:^{14}N ratio analyzed on a Finnigan MAT Delta C mass spectrometer coupled to a Carlo Erba 1108 elemental analyzer. Nitrate and ammonium in soil extracts and plant samples were determined with a continuous flow analyzer (AA-III, Bran & Luebbe, Hamburg, Germany).

Preliminary results

Rice yield and water-use efficiency at three locations

In the 2001 experiments in Beijing, Nanjing, and Guangzhou, yields in the GCRPS plastic film cover plots were 11–31% lower than in the traditional paddy rice plots (Table 1).

Water consumption was higher in Beijing than in Nanjing and Guangzhou as a result of soil type, groundwater level, and evaporative demand. In Beijing, soil texture is much more sandy and the groundwater level is about 40 m, while only 1 to 2 m in Nanjing and Guangzhou. Moreover, air humidity in Guangzhou is higher than in Beijing and Nanjing, leading to a lower evaporative demand. Hence, environmental conditions resulted in lower daily water consumption and higher water-use efficiency in Guangzhou than in Beijing and Nanjing (Table 2). Water consumption in the GCRPS treatments was 60% of that in paddy rice in Beijing. Water-use efficiency, based on net water input (irrigation plus precipitation minus runoff, but not including groundwater input in Nanjing and in Guangzhou) in the GCRPS treatments, was 54%, 238%, and 8% higher than that of the traditional paddy rice production system in Beijing, Nanjing, and Guangzhou, respectively (Table 2).

Table 1. Average regional rice yields and yields from the experiments at three locations, Beijing, Nanjing, and Guangzhou in 2001 (t ha^{-1}).

Location	Average yield in region	Yield in the experiment	
		Paddy	Plastic
Beijing	7.5	8.35 (100)[a]	5.75 (31)
Nanjing	9.0	9.57 (100)	8.52 (11)
Guangzhou	8.0	9.53 (100)	8.23 (14)

[a]Numbers in parentheses indicate percentage reduction in yield compared with paddy treatment. Rice type in Beijing was japonica, while indica types were used in Nanjing and Guangzhou.

Table 2. Water balance and water-use efficiency (WUE) at three locations.

Parameters	Beijing		Nanjing		Guangzhou	
	Paddy	Plastic	Paddy	Plastic	Paddy	Plastic
Irrigation (mm)	3,750	1,275	1,666	99	420	308
Precipitation (mm)	390	394	462	462	770	787
Runoff (mm)	0	0	0	0	471	518
Net input (I + P – R, mm)[a]	4,140	1,669	2,128	561	720	577
Daily water consumption based on net input[a] (mm d^{-1})	30.2	10.8	21.7	3.9	7.7	4.6
Water requirement based on irrigation (m^3 kg^{-1})	4.55	2.22	1.75	0.12	0.50	0.43
Water requirement based on net input[a] (m^3 kg^{-1})	5.02	2.90	2.23	0.66	0.86	0.80
WUE based on irrigation water (kg m^{-3})	0.25	0.45	0.57	8.56	2.02	2.35
WUE based on net input[a] (kg m^{-3})	0.22	0.34	0.45	1.52	1.16	1.25

[a]Not including input of groundwater in Nanjing and Guangzhou.

Options for improving rice yield of GCRPS treatments, particularly in Beijing

In Beijing, no significant difference was observed in 1,000-grain weight (TGW), panicle length, and grain number per tiller among treatments T1, T2, T3, and T4 (Table 3). The number of productive tillers, however, in T2 was 43% lower than in the paddy treatment T1. This lower tiller number was probably one of the main reasons for the 31% lower grain yield than in the traditional paddy rice.

Table 3. Agronomic parameters at the experimental site in Beijing, 2001.

Treatment[a]	Tiller no. (10^6 ha^{-1})	1,000-grain weight (g)	Grains $tiller^{-1}$ (g)	Harvest index
T1	5.62 ± 0.52[b]	20.4 ± 1.0	1.53 ± 0.22	0.38 ± 0.02
T2	3.21 ± 0.13	21.1 ± 0.7	1.83 ± 0.03	0.40 ± 0.01
T3	2.81 ± 0.54	18.0 ± 0.9	1.30 ± 0.24	0.32 ± 0.02
T4	2.99 ± 0.11	20.0 ± 0.6	1.42 ± 0.11	0.39 ± 0.01
T5	2.54 ± 0.38	30.8 ± 0.4	2.42 ± 0.38	0.50 ± 0.01
T6	2.54 ± 0.16	30.6 ± 0.3	2.23 ± 0.22	0.45 ± 0.01

[a]T1 = traditional paddy rice production system; T2 = paddy rice cultivated under aerobic conditions, soil surface covered with plastic film; T3 = surface covered with mulch; T4 = surface not covered; T5 = upland rice variety cultivated under aerobic conditions; T6 = upland rice variety cultivated under aerobic conditions, surface covered with plastic film. [b]Numbers indicate standard deviation of three replications.

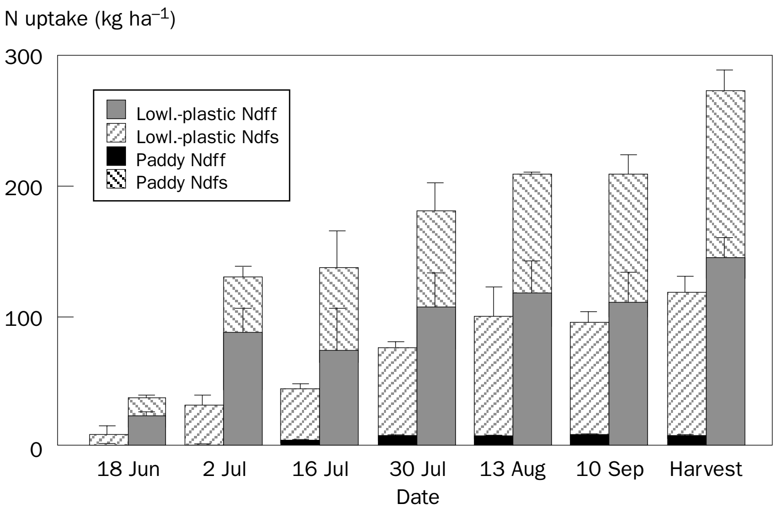

Fig. 2. Accumulated N uptake from fertilizer (Ndff) and from soil (Ndfs) of the GCRPS and the paddy treatment. The total amount of N fertilizer application of both treatments was the same, while there was a single application at the start in the GCRPS and a split application of 40%, 30%, and 30% as basic fertilization, at the beginning of tillering, and at the booting stage in the paddy treatment.

Unexpectedly, nitrogen-use efficiency in the GCRPS treatments was lower than that in the paddy rice treatment at all three locations. Nitrogen uptake of ^{15}N-fertilizer (Ndff) in the GCRPS treatments was much lower than in the paddy rice treatment, whereas nitrogen uptake from soil (Ndfs) of both treatments was similar (Fig. 2). On the other hand, the mineral nitrogen content in the soil solution one and a half months after fertilizer application was less than 20 mg kg^{-1} at different soil depths in the GCRPS treatments (Fig. 3). The lower soil mineral nitrogen content in the GCRPS treatments is due to rapid nitrification under aerobic conditions and frequent irriga-

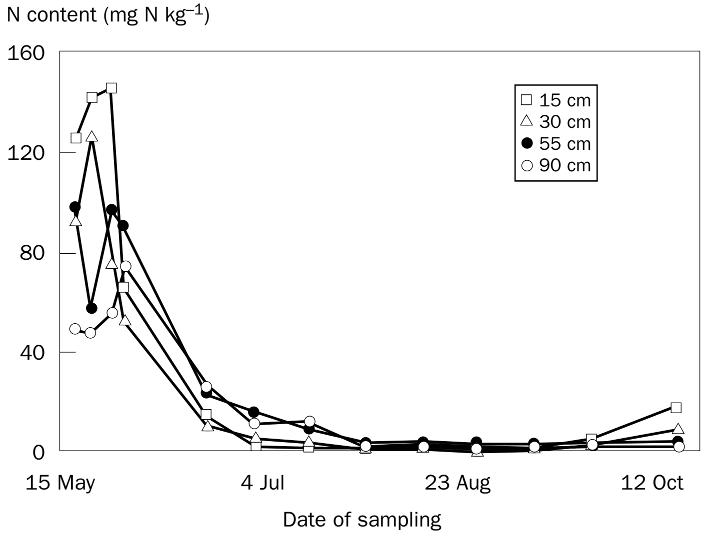

Fig. 3. Time course of mineral nitrogen content of soil solution at different depths in the GCRPS (after Y.F. Wang and J. Gao, 2001, unpublished).

tion that leads to appreciable nitrate leaching, particularly in Beijing. This was confirmed by lower plant nitrogen contents. Hence, the GCRPS conditions resulted in nitrogen deficiency during the late vegetative period, with the consequence of lower tiller numbers. Another reason for the lower tiller number could be the relatively low soil water content in the GCRPS treatments during the tillering stage, when the soil was kept at 70–90% of soil water-holding capacity. Additionally, Mn content in the GCRPS plants was lower than the critical level, whereas the Mn content of the paddy rice was 300 mg kg^{-1} (Fig. 4).

Conclusions

According to the results of the first year at three locations, the ground-cover rice production system reduced water consumption by 60% and increased water-use efficiency by 54% compared with the traditional paddy rice production system in Beijing, while yield decreased by about 11–31%. Lower productive tiller number and lower nitrogen-use efficiency because of the method of fertilization might be responsible for the decrease in yield. Two reasons are possible for the lower productive tiller number and yield under GCRPS: (1) relatively low soil water content (70–90% of soil water-holding capacity) during the tillering period; (2) nitrogen deficiency: no N topdressing under GCRPS vis-à-vis N topdressing in the paddy control during the tillering and booting stages. This was confirmed by lower N_{min} concentrations in the soil solution 1.5 months after N fertilization and a lower Ndff value in the GCRPS treatments. The lower soil N_{min} was caused by rapid nitrification under aerobic conditions and the frequent irrigation that resulted in appreciable nitrate leaching. Micro-

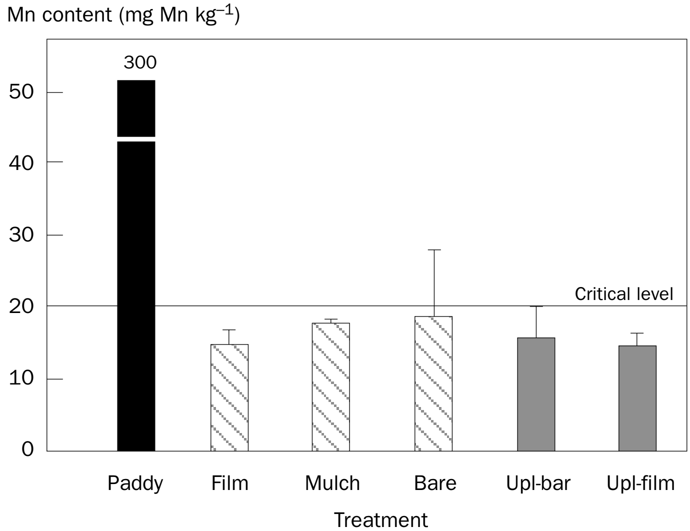

Fig. 4. Mn content of rice leaf, 99 days after planting (13 August 2001) in Beijing.

element deficiency and probably nematode problems could be another reason for the lower yield under GCRPS.

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Saving water with ground-cover rice production systems (GCRPS) at the price of increased greenhouse gas emissions?

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Greenhouse gas emissions of two water-saving ground-cover rice production systems (GCRPS) and a conventional flooded rice (*Oryza sativa* L.) production system were compared in three field experiments in China. In combination with reduced irrigation, plastic film (0.014 mm) and straw soil covers were evaluated in three major water-scarce lowland rice production regions in northern (Beijing), eastern (Nanjing), and southern China (Guangzhou, late rice).

In all three regions, first results showed a pronounced effect of altered water management on greenhouse gas emissions. CH_4 emissions from GCRPS were low at all locations. The exception was Guangzhou, where heavy rainfall raised soil water contents during early growth and induced high initial CH_4 emissions.

N_2O emissions were adversely affected by GCRPS. With both cover materials, increased N_2O emissions were measured and these emissions were closely linked to N fertilization events. With respect to the different global-warming potentials of CH_4 and N_2O, the importance of CH_4 declined and N_2O became the most important greenhouse gas in this first experiment. Overall, a small increase in the contribution to global-warming can be expected. Within the ongoing project, management of nitrogen fertilizer will be optimized for good rice yield and to mitigate N_2O emissions.

During the next decades, water scarcity will be one of the major economic, social, and ecological problems in Asia. In China, measures to save water have been used for more than 40 years. During the same period of time, paddy rice production increased from 56 to 180 million tons per annum (FAO 2002). So, despite these measures, the total water demand for rice continued to grow. Now, water scarcity affects large areas and economic as well as agricultural development are slowed down (Li 2001). Among the most severely affected regions, the North China Plain is facing dramatic shortages (Wang and Zhou 2000), forcing farmers to move to crops less attractive than rice. Rice production systems that do not rely on flooded soil are urgently needed. Such water-saving rice production methods have been developed in China and in other water-limited environments, for example, in Indonesia and in the Indo-Gangetic rice-wheat belt (Liang et al 1999, Kitamura 1986). In the North China Plain, the most promising options include alternating wetting and drying (AWD), aerobic rice (Wang et al, this volume), and ground-cover rice production systems (GCRPS), also called "plastic film mulched dryland rice" (Liang et al 1999). GCRPS have been reported to use only 40% of the amount of water usually needed to grow rice in submerged conditions, while grain yields remain at 90% of those of the high-yielding submerged systems (Liang et al 1999). High and stable yields are two of the major requirements when water-saving systems are developed, or improved.

On a global scale, trace gas emissions from lowland rice fields make a substantial contribution to global warming. Initially, methane had been identified as a major greenhouse gas emitting from paddy rice, and this production system is currently seen as one of the most important anthropogenic sources of CH_4 (Augenbraun et al 1999, IPCC 1996). The effect of paddy rice production on nitrous oxide (N_2O) production is less clear. The strong anaerobic conditions of the bulk soil of paddy rice fields force soil microorganisms to break down soil organic matter anaerobically. While such conditions strongly promote CH_4 production, they might also limit N_2O emissions because, in the bulk soil, the ammonium or urea nitrogen fertilizers typically used are never converted into oxidized products or intermediates.

In contrast, when water-saving management is applied, soils may temporarily dry out to some extent and more aerobic conditions may prevail, leading to a change from anaerobic fermentation to aerobic turnover of organic matter by soil microorganisms. CH_4 production is retarded, CH_4 emissions may decline, and CH_4 may even be consumed by CH_4-oxidizing bacteria (Wassmann et al 2000). In contrast, N_2O emissions may be elevated under temporarily nonsubmerged conditions (Abao et al 2000). Temporary oxygen availability allows for NH_4 oxidation (nitrification), also resulting in the production and emission of N_2O. Water management of lowland rice fields is therefore a crucial factor affecting emissions of the two most relevant trace gases (CH_4 and N_2O) in quite different ways.

In addition to the general evaluation (Shan Lin et al, this volume) of the new water-saving ground-cover rice production system (GCRPS), the objectives of the present study were (1) to monitor greenhouse gas emissions of two types of GCRPS (plastic film cover and straw mulch cover) compared with conventional lowland rice production and (2) to improve our understanding of the effects that these systems have on soil processes. This knowledge will be used for further improving water-saving management systems to maintain or even reduce the effects on global warming.

Materials and methods

Field experiments with an identical layout were installed along a north-south gradient: in the north at Beijing, in the east at Nanjing, and in southern China at Guangzhou. Details of the experimental setup of the field experiments are described elsewhere

(Shan Lin et al, this volume). Briefly, field plots of 6 × 12 m were used in triple replication for growing rice, either following the water-saving GCRPS method or under conventionally submerged lowland conditions. In GCRPS, two types of soil cover—thin plastic film (0.014 mm) or straw mulch—were evaluated, permitting maintenance of soil humidity from 70% to 90% water-holding capacity under reduced irrigation. Natural rainfall was kept in the field plots; therefore, temporary natural submergence was allowed to occur in GCRPS (e.g., during the first 3 weeks in Guangzhou). In Beijing and Nanjing, one rice crop is typically grown per year. In Guangzhou, natural rainfall is usually sufficient for the early rice crop, so GCRPS was tested for the second, late rice crop planted in August.

Urea fertilizer was used at all three locations at 225 kg N ha^{-1}. For the traditional paddy system, the rate was split into three dressings and, for GCRPS in Beijing and Guangzhou, the full rate was given in a single dressing (see Figs. 1 and 2).

Trace gas emissions were measured periodically using the closed-chamber method (Hutchinson and Mosier 1981). For this purpose, mobile chambers and permanently installed metal frames of 50 × 60 cm and 20-cm depth were used. In paddy fields, gas-sampling plots were accessed through permanently installed wooden pathways to avoid forcing the ebullition of gas bubbles.

Gas-sampling protocols were adapted from the recommendations of Buendia et al (1998). Additionally, for adequate measurements of N_2O emissions after fertilization, gas emissions were sampled daily for the first 10 d after nitrogen was applied. Gas samples were collected either in disposable syringes equipped with three-way valves (Braun Melsungen, Germany) or in gas bags. Four consecutive samples were taken in each plot every 10 min. Gas chromatographic measurements of CH_4 and N_2O were completed within 1 week following field sampling.

Results

Large differences in CH_4 emissions were found among the three regions (Fig. 1), so different scales were used. In Beijing (Fig. 1A), only the submerged fields showed CH_4 emissions at a low level, whereas in GCRPS emissions were negligible or even slightly negative for short periods of time. Similar to Beijing, in Nanjing only the submerged control plots showed CH_4 emissions, and in GCRPS only two short events with very low emissions were observed. The general emission level was almost tenfold higher than in Beijing. In Guangzhou, all plots showed very high initial emissions of up to 48 mg CH_4 m^{-2} h^{-1} for about 4 weeks, then emissions from GCRPS declined to low levels. From the submerged control plots, continuous rates of 7–8 mg CH_4 m^{-2} h^{-1} were emitted for prolonged periods.

In contrast to CH_4 emissions, the general magnitude of N_2O emissions from the three experimental regions was in a similar range (Fig. 2). In Beijing (Fig. 2A), one period of high emissions, following the single 225 kg N ha^{-1} fertilization, was the dominating event in GCRPS. A peak of up to 1.5 mg N_2O m^{-2} h^{-1} was observed. In Nanjing, fertilizer application followed a different pattern (indicated by vertical arrows in Fig. 2B). Thus, in GCRPS, two emission events were observed during the

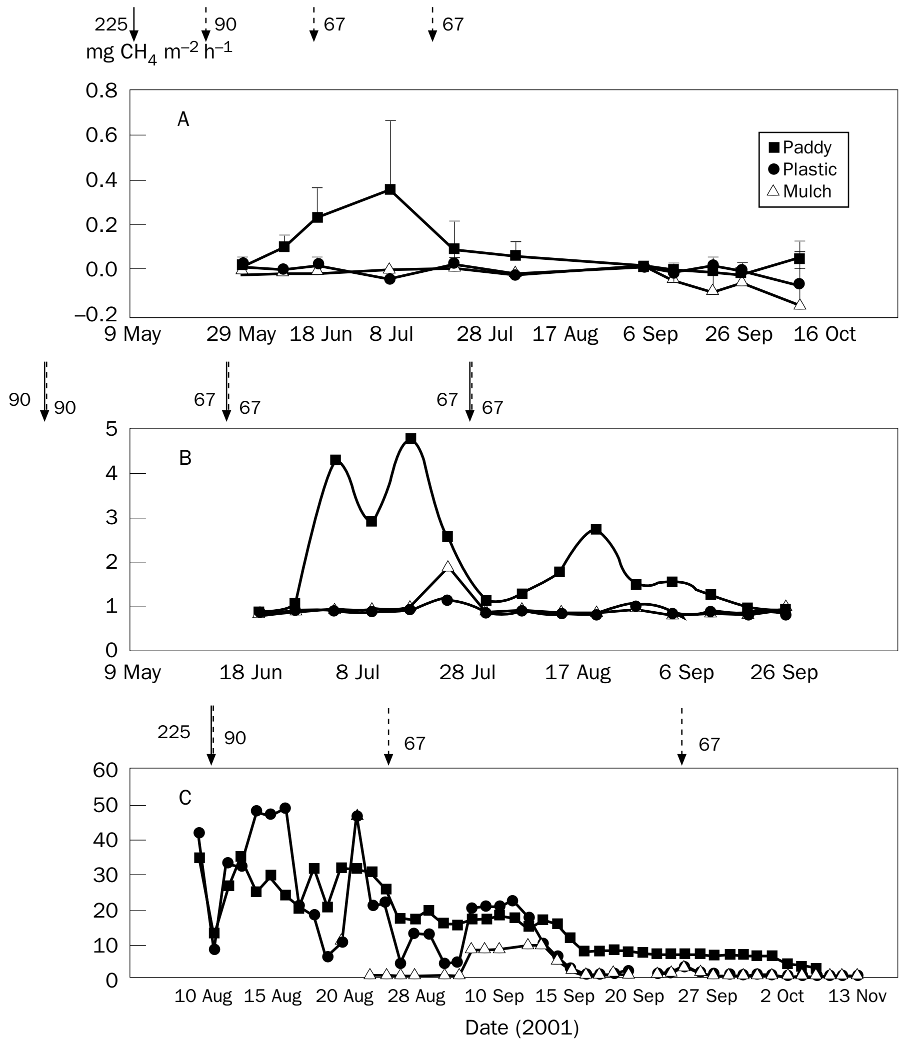

Fig. 1. Time course of methane (CH_4) emissions from field experiments in Beijing (A), Nanjing (B) measured at 1800, and Guangzhou (C), mean of 0600, 1200, and 1800 measurements. Fertilizer additions are indicated by vertical arrows, with full-line arrows indicating dressings in the GCRPS treatments and dotted arrows standing for dressings in the "paddy control" treatment. Numbers next to arrows indicate the respective fertilizer rates (kg N ha^{-1}).

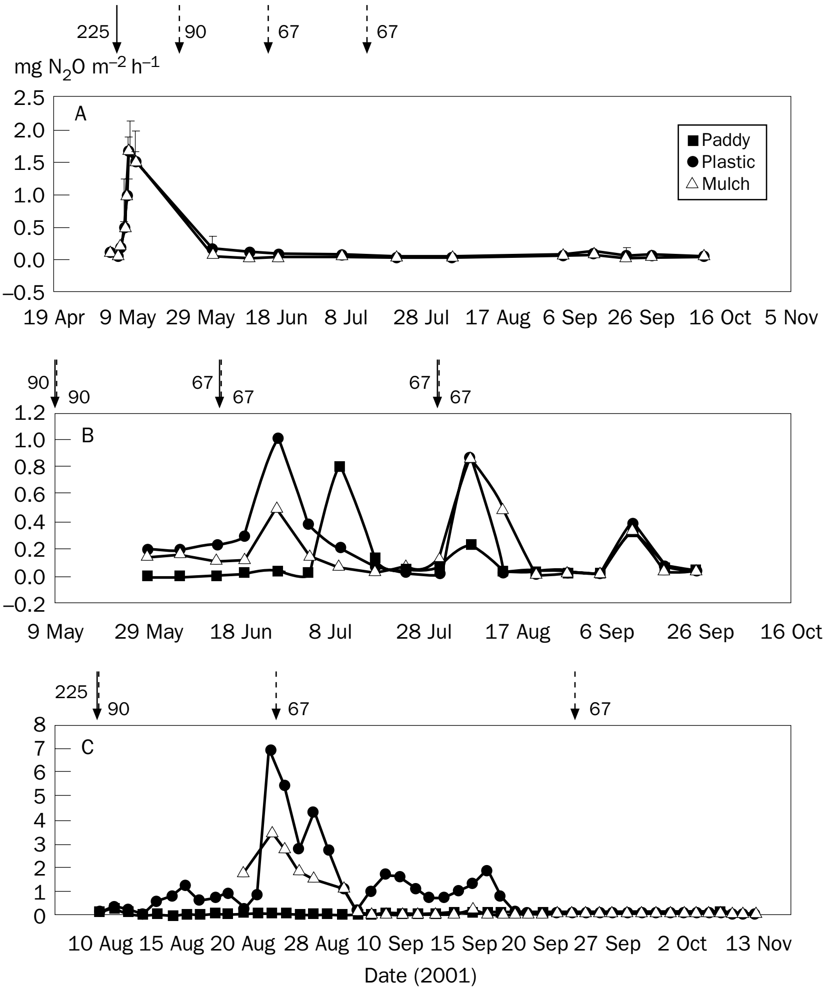

Fig. 2. Time course of nitrous oxide (N_2O) emissions from field experiments in Beijing (A), Nanjing (B) measured at 1800, and Guangzhou (C), mean of 0600, 1200, and 1800 measurements. Fertilizer additions are indicated by vertical arrows, with full-line arrows indicating dressings in the GCRPS treatments and dotted arrows standing for dressings in the "paddy control" treatment. Numbers next to arrows indicate the respective fertilizer rates (kg N ha^{-1}).

experimental period. These events immediately followed fertilizer applications 2 and 3. Probably after fertilizer dressing no. 1, a first peak was missed out in our study because there was a short delay in the onset of gas emission measurements in Nanjing. In Guangzhou, southern China (Fig. 2C), GCRPS plastic film showed substantial N_2O emissions 6 weeks after fertilizer application, while emissions from GCRPS straw mulch were low. In the submerged control fields, almost no emissions were observed.

Discussion and conclusions

The water-saving ground-cover rice production system led to major changes in trace gas emission processes in lowland rice soils. Overall at the three sites studied, CH_4 emissions from GCRPS decreased substantially, whereas N_2O emissions increased markedly. The magnitude of these changes was quite different in the three Chinese regions studied.

CH_4 emissions

The strong decline in CH_4 emissions produced by the reduction in soil water contents to 70–90% water-holding capacity in GCRPS is one of the most striking results of this study. Evidently, short-term soil aeration between irrigation cycles prevented the development of low redox potential in soil, which is a requirement for CH_4 production. Additionally, on the loamy sand soil in Beijing, the high rates of freshwater that percolated through the soil profile were an important contributing factor (Yagi et al 1998) in further reducing CH_4 emissions at this location. Only in Guangzhou, during the first 3–4 weeks after the start of the experiment, when heavy rainfall submerged all the experimental fields, were considerable CH_4 emissions observed from the GCRPS plots. Generally, the level of CH_4 emissions in Guangzhou was remarkably high compared with that of other studies in lowland rice areas (Cai et al 1997). We hypothesize that this can be attributed to the decay of plant residues remaining in the soil from the early rice crop, grown in the same field until about 2 weeks before transplanting/ direct seeding of the late rice crop.

Organic amendments have been reported to promote CH_4 emissions from lowland rice fields kept under submerged conditions (Bronson et al 1997, Corton et al 2000). In contrast to these studies, "GCRPS straw mulch" had no effect on CH_4 emissions in our first year's evaluation. Emissions from "GCRPS plastic film" and GCRPS straw mulch were not significantly different and no trends were evident (Fig. 1). It seems likely that the lack of submergence was the dominant factor in GCRPS, and this prevented any other effects of straw in terms of an additional carbon source.

N_2O emissions

N_2O emissions were adversely affected. Although GCRPS led to a general reduction in CH_4 emissions, N_2O emissions increased markedly. In Beijing, the balance of N_2O emissions from GCRPS fields was strongly dominated by the initial fertilizer applications. After this initial period, the N_2O emissions decreased to very low levels, and in the late growing period slightly negative emissions indicated some consumption of N_2O. The experiments in Nanjing and Guangzhou showed similar effects of GCRPS on N_2O emissions. The lack of submergence and soil coverage with both materials tested (plastic film and straw mulch) led to an increase in N_2O emissions compared with submerged fields. In Nanjing, where fertilizer was applied in a different pattern, fertilizer applications were responsible for the increased emission patterns observed. Maximum amounts of N_2O were emitted 5–8 d after fertilizer application, which is in agreement with results on total denitrification losses from rice fields (Buresh et al 1991). In Guangzhou, some decoupling of N_2O emissions and fertilizer timing was found. Immediately after fertilization, no or only very low emissions occurred and the peaks in emission occurred after a delay of about 14 d. As with the pattern of CH_4 emissions in Guangzhou, we assume that this phenomenon was related to the initial paddy-type conditions that prevailed in all GCRPS fields, and that resulted from the heavy rainfall at the start of the experimental period.

Impact on global warming and outlook

To assess the net effect of the water-saving GCRPS method on greenhouse gas emissions, the global-warming potentials of CH_4 and N_2O (IPCC 1996) should be considered. Generally, the more temperate conditions in Beijing and Nanjing led to lower emissions at those two sites (Figs. 1 and 2). Nevertheless, the results of our first year's experiment provide evidence that, at all three sites, GCRPS led to an increase in the effects of lowland rice production on global warming. This was due exclusively to the higher N_2O emissions after fertilizer applications. Future research on GCRPS and also on water-saving rice production in general should therefore include fertilizer management studies to maintain good yields and to reduce N_2O emissions.

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Rice-wheat

Adopting conservation agriculture in the rice-wheat system of the Indo-Gangetic Plains: new opportunities for saving water

R.K. Gupta, R.K. Naresh, P.R. Hobbs, and J.K. Ladha

Agricultural policy in the 1960-70s focused on achieving food security through increased coverage of high-yielding varieties, expansion of irrigation, and increased use of external inputs. This enabled rice-wheat to emerge as a major cropping system in the Indo-Gangetic Plains (IGP), ushering in the "Green Revolution" (GR). GR technologies have remained the cornerstone of the South Asian strategy for food security, rural development, conservation of natural resources, and poverty alleviation. Evidence is now appearing that the rice-wheat system has weakened the natural resource base. The growing realization that agriculture of the post-Green Revolution era will be guided by the need to produce more better-quality food from more marginal-quality land and water resources, besides sustaining environmental quality, only adds to the challenge. Thus, the major challenge for the Rice-Wheat Consortium countries is to develop a rice-wheat system that produces more at less cost and improves profitability and sustainability. This suggests that agriculture in consortium countries needs an infusion of new technologies that are able to tap new sources of productivity growth and are more sustainable.

On the basis of driving variables for agricultural development, the IGP have been delineated into five relatively homogeneous transects to address location-specific rice-wheat system ecology problems. Thematic issues of crop improvement, water management, nutrient management, weed and pest management, and policy research are integrated with crop establishment and tillage, which are at the center of all agronomic and crop management practices developed for the RW system ecology within each transect for sustained production, diversification, and enhanced system productivity. This paper will describe in a matrix the relative potential of improved technologies, particularly in relation to water savings and water-use efficiency.

Cropping intensity in any region depends on the soil and bioclimatic conditions, the socioeconomic situation of the farmers, and opportunities for marketing surplus production. Although rice and wheat crops have been grown for more than 1,000 years in South Asia, the RW system was generally developed by introducing rice in traditional wheat-growing areas and vice versa (Paroda et al 1994). Now, most of the RW system is found in subtropical and warm-temperate regions of South and East Asia characterized by warm wet summers and cool dry winters. It extends across the IGP spanning Pakistan, through Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, and the Terai of India and Nepal into Bangladesh. Timsina and Connor (2001) reported that nearly 85% of the RW system of South Asia is located in the IGP. The remaining RW system is practiced in several other parts of the Indian subcontinent outside the IGP in Madhya Pradesh, Himachal Pradesh, southwestern parts of India, and the Brahmaputra flood plains of Assam and Bangladesh. Since the national agricultural crop statistics reported in the region are published by individual crops and not by cropping systems, and there are spatial and temporal variations among crops, most estimates of RW area are subjective (Timsina and Conner 2001, Yadav et al 1998, Paroda et al 1994, Hobbs and Morris 1996). The situation is further complicated because whereas some farmers grow rice and wheat on the same plot in the same year, others grow break crops in between rice and wheat in different years, and also in different plots. Thus, estimates of RW area vary from study to study. However, most researchers seem to agree that rice and wheat together contribute more than 70% to the total cereal production and the relative importance of the RW system varies among countries. The estimated area of the RW system in India, Pakistan, Bangladesh, and Nepal is about 10.0, 2.2, 0.8, and 0.5 million ha, respectively, totaling 13.5 million ha (Ladha et al 2000). Keeping in view the population pressure and that good land is being diverted to other sectors of national economies, the prospects for further expansion of rice and wheat area seem remote (FAO 1999) and additional sources of productivity growth in RW would have to come through newer technological interventions that enhance overall yields and system productivity.

Characteristics of the IGP and RW system

On the basis of driving variables for agricultural development, the IGP have been delineated into five relatively homogeneous transects to address location-specific RW system ecology problems. Thematic issues of crop improvement, water management, nutrient management, weed and pest management, and policy research are integrated with tillage and crop establishment, which are at the center of all agronomic and crop management practices developed for the RW system ecology within each transect for sustained production, diversification, and enhanced system productivity. This paper will describe in a matrix the relative potential of improved technologies across the IGP by thematic issue (Table 1).

The IGP are a relatively homogeneous ecological region in terms of vegetation but it can be subdivided into five broad transects, based primarily on physiographic and bioclimatic factors. The Trans-Gangetic Plains (regions 1 and 2) occupy large

Table 1. Matrix of options for establishment of rice and wheat crops in the system.

System Planting methods:	Rice			Wheat	
	Puddled (flat land)[a]	Unpuddled (flat land)	Raised beds	Flat land	Raised beds
Direct-seeded					
Zero-till/controlled traffic/ paired-row	No	Yes	Yes	Yes	Yes
Reduced till	No	Yes	Yes	Yes	Yes
Sprouted seed (drum seeder)/surface seeding	Yes	Yes	Yes	Yes	Yes
Transplanted					
Manual	Yes	Yes	Yes	No	No
Mechanical transplanter	Yes	Yes	Doubtful	No	No
Broadcast seedlings	Yes	Yes	Yes	No	No

areas of east and west Punjab and Haryana, in Pakistan and India, respectively. Transects 3 and 4 comprise the areas of the upper and middle Gangetic Plains in Uttar Pradesh (UP), Bihar, and the Terai of Uttaranchal in India and Nepal. The lower parts of the Gangetic Plains in West Bengal, India, and parts of Bangladesh constitute transect 5.

The IGP have a continental monsoonal climate. In the northwest Trans-Gangetic Plains, the average annual precipitation ranges from 400 to 750 mm y^{-1} and increases toward the Bay of Bengal. In warm and humid transect 5, constituting parts of the lower Gangetic Plains of West Bengal and Bangladesh, annual rainfall is as high as 1,800 mm y^{-1}. Nearly 85% of the total precipitation is received during the monsoon season from June to September. In winter months, only a few showers are received from December to February.

The IGP gradually slope from the northwest toward the Bay of Bengal and toward the Arabian Sea in the Indus Plains. There are wide variations in soil types, generally coarser in the Trans- and Upper-Gangetic plains and becoming finer downstream of the river systems. Soils are primarily calcareous micaceous alluviums with sandy loam to loam soil in the upper reaches and becoming finer-textured in the distal plains. In humid and subhumid plains, micaceous sediments are slightly acidic and crops grown on them respond to the application of phosphorus, lime, zinc, and boron. Most soils in the IGP are deficient in nitrogen, phosphorus, and zinc. Because of the micaceous nature of soils, the use of potassic fertilizers has been avoided for a long period but now deficiency of potash is emerging in several areas. Iron deficiency can be seen in rice nurseries if no organic fertilizer is used.

A significant observation not reflected by the above description is the greater reliance of farmers on tubewell irrigation in the northwestern parts of the IGP. Excessive groundwater development in freshwater aquifer zones has led to a drop in the water table and to a rise in the water table in areas underlain with low-quality aquifers having problems of residual alkalinity, a high sodium adsorption ratio, and/or excess salts. Low-quality waters are interspersed with good-quality aquifers in many areas of the northwest IGP and are being used successfully in crop production by farmers (Gupta et al 1994) (Fig. 1). More than 2.5 million ha of alkali soils that occupied large areas in the northwest in the 1970s are now at various stages of reclamation. The RW system is a preferred choice during the initial reclamation stages of alkali soils (Gupta and Abrol 1990). In the northwest, the RW system is highly mechanized, input-intensive, and dependent on the conjunctive use of surface water and groundwater. In contrast, the RW system of the eastern IGP is labor-intensive and less mechanized and farmers use low inputs because of serious problems of drainage congestion and rainwater management (Velayutham et al 1999, FAO 1999). The farm holdings are larger in the northwest than in the eastern region, which has a greater number of resource-poor farmers.

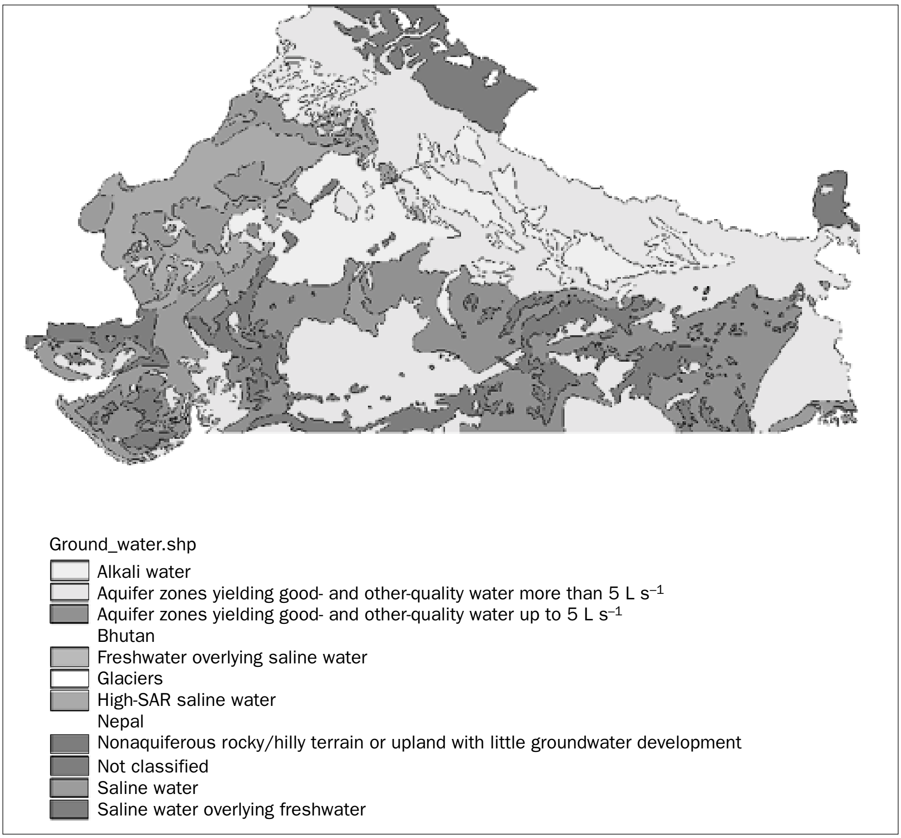

Fig. 1. Groundwater quality in the IGP (Gupta at al 1994).

Wheat (*Triticum aestivum, T. durum*) is cultivated during the cool dry winter season (November to April). Rice (*Oryza sativa* L.) is grown during the warm humid/subhumid monsoon season (June to October). Traditionally, wheat has been cultivated for a long time in the northwest and rice in the eastern IGP. Irrigated and rainfed agriculture coexist in most districts. This has led to a mosaic pattern of agricultural development in the IGP. Many farmers in the northwest IGP grow mungbean between wheat and rice crops. To overcome herbicide resistance to isoproturon in *Phalaris minor,* farmers replace wheat with Indian-mustard, sugarcane, or berseem. In India and Pakistan, farmers intercrop mustard/rape with several rows of wheat. Many Nepalese farmers grow soybean on the peripheral bunds of rice fields. In the eastern parts of the IGP in Uttar Pradesh, Bihar, West Bengal, and Bangladesh, many farmers grow three rice crops in a year, namely, the *aus* (April to July), *aman* (July to November), and *boro* rice crop (November to April). Boro rice is generally grown in poorly drained lower positions of the landscape with provision for irrigation. In low-lying areas of eastern Uttar Pradesh and Bihar (India), parts of Bangladesh, and Jiangsu Province of China, where water recedes late or soils remain wet for a long time, farmers seed lentil, peas, and wheat on drying paddies a couple of days before the harvest of rice (Razzaque et al 1995, Timsina and Conner 2001, Gupta et al 2002). Compared to the northwestern IGP, eastern farmers diversify the RW system more to cover risk of drought- and flood-prone agriculture. Many farmers replace wheat with oilseeds (*Brassica juncea* or *napus*), pulses (pea, *Pisum sativum*), grass pea (*Lathyrus* spp.), chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), potato, or sugarcane and they occasionally replace rice with pigeonpea (*Cajanus cajan*), maize, sunflower, soybean, and sorghum. Winter maize is also popular in eastern parts of the Gangetic Plains in Bihar, Uttar Pradesh, and Bangladesh.

Compared to the northwest, summers begin early in the east and average temperatures are higher. This reduces the length of the growing season of wheat. To improve wheat productivity, it is thus crucial that rice be harvested early in the winter season in the eastern IGP. Farmers often combine long-duration rice cultivars with short-duration wheat cultivars in the eastern IGP.

Sustainability dimensions

In the RW cropping system, the two crops have contrasting edaphic requirements. Whereas rice is commonly transplanted into puddled soils and gets continued submergence, wheat is grown in upland well-drained soils having good tilth. Puddling reduces infiltration of water but destroys soil structure. Expecting a better wheat crop, farmers generally plow 6–8 times after the rice harvest to achieve a good seedbed for wheat. However, excessive tillage results in late planting and reduced yields of wheat. Estimates from the Punjab, India, are that wheat grain yield declines nearly 1.5% per day of delay in sowing of wheat after the second week of November (Ortiz-Monasterio et al 1994). The yield losses are much more (about 63 kg d^{-1} ha^{-1}) in eastern parts of the Gangetic Plains. Timely planting of crops also has the advantage that untimely rains do not interfere with harvesting-threshing operations for wheat.

Besides late planting, key problems of the RW system are declining factor productivity and yield levels way below the potential productivity of the system, nutrient mining, and the emergence of multiple nutrient deficiencies (Duxbury et al 2000). The turnaround time between rice and wheat crops is 3–6 weeks. To timely plant wheat, many farmers harvest the rice crop with a combine and burn loose residues. Burning releases greenhouse gases and particulate matter in large quantities in sudden spurts. This deteriorates air quality and results in significant losses of nutrients (Sharma and Mishra 2001).

In the semiarid northwest, excessive groundwater use for irrigation has led to receding water tables. In the eastern IGP, the delayed onset of rains and almost complete lack of groundwater development during the monsoon season delay rice nursery and transplanting operations, resulting in a vicious circle of late planting of crops. Thus, sustainability concerns of the RW system can be addressed by timely crop planting with good crop and residue management that avoids burning and improves the use efficiency of costly external inputs.

Given the prospect of more early sowing, the question has arisen whether certain cultivars are especially suited to such practices (Mehla et al 2000). Although characteristics such as ability to emerge from a rough seedbed with large amounts of surface residues will also be desirable, an appropriate phenological response seems desirable. Mehla et al (2000) noted that two cultivars favored for timely (early) sowing, WH 542 and PBW 343, have a longer vegetative phase and shorter grain-filling phase than older varieties such as HD 2008 and HD 2329.

Given the weather uncertainty, farmers, particularly in the eastern IGP, adjust fertilizer application according to seasonal water availability. Modern improved varieties of wheat respond well to varying soil fertility levels such that the local cultivars do not outyield them. But this does not seem to be so in rice. Local cultivars outyield improved cultivars at low levels of soil fertility and water supply (AICRP, Saline Water Use 1992). This has an important bearing on nutrient-water interactions, input use, seed replacement rates, and actual yields. We therefore need to examine this germplasm topic.

Tillage and system productivity

Most of the rice in this system is managed by transplanting rice seedlings into puddled soils. This age-old planting method is used to reduce water percolation and help in weed control. On the negative side, puddling degrades soil physical properties, resulting in poor soil physical conditions for establishment of the next upland crop such as wheat. A lot of research in the region has looked at the possibility of establishing rice without puddling. The major hurdle has been the paucity of knowledge on good weed management. Most rice herbicides available in the region have been developed for transplanted rice and these are not as effective in dry-seeded rice. It has been observed that stale seedbed techniques in combination with herbicides and keeping fields submerged early in the season help control chlorosis and weeds. Experiments conducted at Pantnagar and Bhairahawa, Nepal, on total RW system productivity showed that tillage and puddling don't have much influence on rice yields. Wheat yields were affected by the various tillage options whether applied in the rice season or in the wheat season. Wheat yields were significantly better when rice soils were not puddled at both sites. Rooting was involved in this difference. Essentially, wheat did worse when the soils were puddled and conventionally tilled.

Water use

The irrigation water requirement of rice and wheat has been studied at different locations in the IGP under the All India Coordinated Research Project on Water Management. The total water requirement for wheat has been estimated to fluctuate from 238 mm in Bihar to 400 mm in Punjab. The total water requirement of rice is estimated to vary from 1,144 mm in the Bihar plains to 1,560 mm in Haryana. Thus, a total of 1,382 to 1,838 mm of water is required for the RW system at different locations in the IGP, accounting for more than 80% for the rice-growing season. Tripathi (1990) studied the components of water balance under continuous submergence in texturally variant rice fields at Pantnagar. He reported that the total water requirement ranged from 1,566 mm in clay loam soil to 2,262 mm in sandy loam soil, with the variations primarily caused by deep percolation losses (Table 2). Thus, to save on water, savings must be made during the rice-growing season, the major water user in the RW system.

Long-distance interbasin transport of surface water for irrigating the RW system of the IGP is a common feature. Large surface irrigation systems employ the warabandi method of water allocation and distribution. Provision of surface irrigation has altered the spatial regional salt and water balances in the IGP. Irrigation with snow-melt waters having an average electrical conductivity of 0.3 dS m^{-1} increases the salt load of the soil by nearly 2 Mg ha^{-1} y^{-1} under the RW system. There is little information on the amount of salt removal from this IGP basin through a network of river systems. Some estimates suggest that only 27% of salts are removed from the Indian parts of the IGP. Many farmers believe that land quality is deteriorating in many parts of the irrigation commands. Besides increasing the salt content of the soil

Table 2. Irrigation requirement of rice and components of water loss (mm) under continuous submergence in texturally variant soils.

Particulars	Clay loam	Silty clay loam	Loam	Sandy loam
Irrigation requirement (mm)	1,125	1,200	1,500	1,775
Effective rainfall (mm)	358	402	495	485
Total water requirement (WR) (mm)	1,566	1,657	1,955	2,262
Percolation as % of total WR	57.0	52.5	60.0	66.9
Evapotranspiration as percent of WR	44.0	44.2	41.3	32.9

Source: Tripathi (1990).

profile, irrigation has differentially affected the groundwater table conditions in the head- and tail-end reaches of the irrigation commands. The quality of irrigation systems leaves much to be desired. As a consequence, reliance on groundwater is increasingly greater. Future food security in this region is severely threatened by unsustainable groundwater use and inappropriate water management practices. The main problems are twofold: rising groundwater tables in areas underlain with low-quality aquifers, leading to secondary salinization and waterlogging, and falling water tables because of overpumping of groundwater in good-quality aquifer zones.

Conjunctive use of rainwater/groundwater

Farmers usually make provisions for irrigation water for the wheat crop. For this reason, irrigated area is much higher for wheat than for rice (Tables 3 and 4). Whereas, in the northwest, rice is cultivated with assured irrigation, farmers in the east generally raise rice crops with rainwater only. Groundwater use is minimal during the main rice season and groundwater is not even used to raise rice seedlings.

The winter season is short in eastern India. Long-term analysis of the rainfall data clearly indicates that there are three distinct periods of moisture availability (Table 5). The early moist period (evaporation exceeds rainfall) extends over 12–18 days, followed by 93–139 d of a humid moist period wherein precipitation exceeds potential evapotranspiration. This is followed by a moist period of 17–22 d in which once again rainfall is less than evapotranspiration. If the rice seedlings and crop can be established early and transplanted in the first moist period, before the humid period, the rice crop can benefit from the monsoon rain and grow without the need for irrigation. Timely transplanting of rice also results in earlier harvests and allows timely planting of the next wheat crop. The results of farmer participatory field trials showed that the strategy of timely transplanting of rice improves wheat yields. RW system productivity was nearly 12–13 t ha^{-1} when rice was transplanted before 28 June. This decreased by more than 40% when fields were planted after 15 August (to 6–7 t ha^{-1}). The key issue is, if a higher system productivity is desired, the rice crop must be planted early with the onset of monsoons by raising rice nurseries with groundwater

Table 3. Percent irrigated area under rice and wheat in the states of the Indo-Gangetic Plains during 1995-96.

State	Percent irrigated area under rice	Percent irrigated area under wheat
West Bengal	27.2	89.3
Bihar	40.2	88.4
Uttar Pradesh	62.3	92.5
Haryana	99.4	98.3
Punjab	99.8	97.1

Source: Agricultural Statistics at a Glance, 1999, Ministry of Agriculture, DAC, Government of India.

Table 4. Percent irrigated area under rice and wheat in 1996.

Area of IGP	Rice	Wheat
Eastern IGP	27.4–65.0	89.0–92.0
Northwest IGP	96.4–99.6	97.4–99.8

Source: Agricultural Statistics at a Glance, 1999, Ministry of Agriculture, DAC, Government of India.

Table 5. Range of rainwater availability periods (days) in different states of eastern transects of the IGP in India.

Transect/state	Moist period I	Humid period	Moist period II
Eastern Uttar Pradesh	12–18	81–123	17–22
Bihar	12–18	95–139	17–22
West Bengal	16–28	130–208	11–22
Water use in field preparations and puddling before transplanting of rice by end of July to middle of August: 400–600 mm		Rice crop ends up in terminal drought; succeeding crop delayed, forced maturity because of short winter, low yields	
(Promoting rice nursery raising with groundwater for timely transplanting in fields having bunds of 20 cm height to conserve 95% of rainwater)			

and vacating the main fields early in the season for the succeeding wheat or other crop. The situation is no different in Bangladesh. The strategy outlined above has been tested in a few hundred hectares of farmers' fields in Bihar and has paid rich dividends.

Studies have indicated that raising peripheral bunds to a height of 18–20 cm around fields could store nearly 90% of the total rainwater *in situ* for improved rice production. The following relationship has been observed to facilitate the conjunctive use of rainwater and to minimize irrigation water application (Mishra et al 1997):

$$RE = 121.75\ e^{-0.181\,h} \qquad R^2 = 0.967 \qquad (1)$$

in which RE is rainfall excess as percentage of rainfall and h is bund height in cm. Timely transplanting of the rice crop can increase rainwater-use efficiency when compared with delayed planting (Fig. 2). The timely transplanting of the rice crop can also increase overall system productivity because of increased subsequent wheat yields.

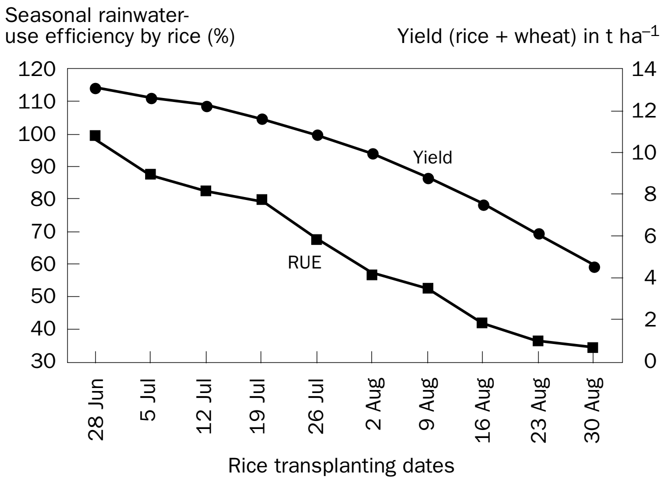

Fig. 2. Seasonal rainwater-use efficiency (RUE) as influenced by time of rice transplanting. (Figure redrawn and based on data adopted from S.R. Singh, ICAR Complex Patna, 2001.)

Intermittent submergence

The age-old practice of puddling rice fields seems to have evolved to aid in transplanting and controlling weed growth. In growing rice under continuous soil submergence, the irrigation requirement varies a great deal among different regions of the IGP on account of variation in rainfall, soil type, evaporative demand, and depth of the water table. Whenever the rainwater is short of meeting the water requirement of a rice field, irrigation water is applied to fulfill the water requirement. Chaudhary (1997) pointed out that a 3-d drainage period, generally suitable, can easily bring about a more than 40% savings in water without compromising rice yields (Table 6).

Precision land leveling

It is by far a rule rather than an exception that most irrigation systems in the Indian subcontinent are unable to assure delivery of water when it is needed and in sufficient quantities. Therefore, most farmers in the IGP rely on irrigating their crops heavily when water is available on the basis of crop phenological stages and visual symptoms of water stress rather than on the basis of soil moisture depletion patterns. Night irrigation is practiced throughout the IGP, which also promotes overirrigation. The other reason for overirrigation relates to poor land leveling. Solving these problems is crucial for effective water savings. The strategy adopted on the premise that all the above problems will be examined by farmers has led scientists to promote scheduling irrigation on the basis of evapotranspiration rates. Apparently, this strategy has not worked well. The same amount of irrigation water can easily be saved by precision land leveling. All the resource-conserving technologies (RCTs) benefit from leveled fields. This is being promoted in Pakistan as a means of improving water efficiency and crop yield through improved nutrient-water interactions. When land leveling is

Table 6. Effect of intermittent irrigation on rice yield and irrigation water requirement at various locations in the IGP.

Location	Soil type	Yield (t ha^{-1})				Savings in irrigation water[b]
		Continuous submergence	Irrigation after drainage period[a]			
			1 day	3 days	5 days	
Pusa (Bihar)	Sandy loam	3.6 (81)	3.5 (60)	3.3 (46)	2.9 (35)	43
Madhepura (Bihar)[c]	Sandy loam	4.0 (35)	–	4.0 (16)	4.0 (11)	54
Faizabad (Uttar Pradesh)	Silt loam	3.8 (65)	2.9 (42)	–	–	–
Pantnagar (Uttar Pradesh)[b]	Silty clay loam	8.1 (121)	7.6 (112)	7.4 (90)	6.9 (60)	44
Ludhiana (Punjab)	Sandy loam	5.5 (190)	5.4 (145)	5.1 (113)	5.2 (96)	40
Hissar (Haryana)	Sandy loam	5.7 (220)	5.2 (196)	4.7 (126)	–	43
Kota (Rajasthan)	Clay loam	5.4 (145)	5.3 (86)	5.1 (68)	–	53

[a]Drainage period in days after disappearance of ponded water. Numbers in parentheses show irrigation water requirement (cm). [b]With 3-day drainage vs continuous submergence. [c]High water-table condition.
Source: Chaudhary (1997).

combined with zero-tillage, bed planting, and nonpuddled rice culture, we have observed that plant stands are better, growth is more uniform, and yields are higher. The use of a permanent bed system and zero-tillage results in less soil disturbance and reduces the need for future leveling. India is also promoting land leveling in Haryana and western Uttar Pradesh

In Pakistan's Punjab, the average water and irrigation cost savings with laser leveling, zero-tillage, and bed planting over the traditional method were 715, 689, and 1,329 m^3 ha^{-1}. This translates into a savings of PRs 522, 503, and 970 ha^{-1} based on a water price of PRs 900 acre-$foot^{-1}$ for private tubewells for 1999-2000 (Gill et al 2000).

Benefits of the RCTs

Farmers are adopting the new RCTs quickly. Nearly 300,000 ha of wheat were grown that way in 2001 and this is expected to increase to a million ha in the next few years. Farmer feedback on water savings with these new technologies essentially says that they save water. For zero-tillage, farmers report about 25–30% water savings (Table 7). This comes in several ways. First, zero-tillage is possible just after the rice harvest and residual moisture is available for wheat germination. In many instances where wheat planting is delayed after the rice harvest, farmers have to preirrigate their fields before planting; zero-tillage saves this irrigation. Savings in water also come from the fact that irrigation water advances quicker in untilled soil than in tilled soil. That

Table 7. Water savings and wheat yield with zero-till technologies in farmer participatory trials.

Parameter	Paired planting[a]	Controlled traffic	ZT[b]	FP-CT
Water savings (%)[c]	26.2	30.8	35.4	–
Yield (t ha^{-1})	6.5	5.8	5.8	5.2

[a]Spacing between set rows (14 cm) and between paired sets (25 cm). [b]ZT = zero-tillage, FP-CT = farmer practice-conventional tillage. [c]Compared with conventionally tilled wheat planted a week later (FP-CT).

means that farmers can apply irrigation much faster (Table 8). Because zero-till wheat takes immediate advantage of residual moisture from the previous rice crop and cuts down on subsequent irrigation, water use decreases by about 1 million L ha^{-1}. One additional benefit is less waterlogging and yellowing of the wheat plants after the first irrigation, which is a common occurrence on normal plowed land. In zero-tillage, less water is applied in the first irrigation and thus yellowing is not seen.

Farmers also report water savings in bed planting. Farmers commonly mention 30–45% savings in this system during the wheat season and even more in the rice-growing season. Farmers also indicate that it is easier to irrigate with bed planting. The question is how to determine timing and how to apply irrigations efficiently with this system. This is being studied in a new RWC-ADB project in India and Pakistan. When beds are kept submerged for the first few weeks, and then irrigation supply frequency is reduced later, farmers are able to save around 30% water and overcome weed and iron chlorosis problems associated with bed-planting systems. We have observed that cultivars of rice and wheat differ considerably in early seedling vigor and chlorosis susceptibility in the bed-planting system. This is being investigated further.

Nutrient-water interactions

In the input-intensive RW ecosystem, where wet-season rice is succeeded by an upland wheat or other high-value upland crop such as vegetables in the dry winter season, a problem of leakage of N into the environment was observed. The N polluted the groundwater aquifers and surface water bodies. Excessive use of N fertilizer in high-value crops is economically motivated. A strategy for including an N-catch crop such as maize or mungbean before the onset of the monsoon is necessary to decrease NO_3 leaching and maximize N-use efficiency. Inclusion of a catch crop in the RW system will affect the irrigation water requirement, residual soil moisture content before rains, and hence rainwater storage and groundwater recharge.

In the raised-bed planting system of rice cultivation in unpuddled soils, farmers have followed the general principle of light and frequent irrigation. How to use N in this system of rice cultivation is yet to be resolved to avoid volatilization losses of N. Whether the entire N can be applied as a basal dose is still a researchable topic. The practice of deep placement of N into the beds and transplanting or direct seeding rice

Table 8. Effect of tillage options on irrigation time, yield attributes, and yield of rice.

Tillage options[a]	Experimental area (ha)	No. of farmers participating in trial	No. of plants m^{-2}	Tillers $plant^{-1}$	Irrigation time ($h\ ha^{-1}$)	Productive tillers $plant^{-1}$	Panicle length (cm)	Grains $panicle^{-1}$	Yield ($t\ ha^{-1}$)
DSRB	14	22	34	24	153	15	22.6	165	5.0
TRB	12	20	35	24	146	19	23.4	173	5.6
DSR (flatland)	12	10	56	16	205	13	21.9	163	5.7
RTR	1.6	7	32	13	216	13	22.6	169	5.2
CT	14	35	27	16	250	12	21.5	163	5.3

[a]DSRB = direct-seeded rice on beds, TRB = transplanted rice on beds, ZTR = zero-tilled rice on flat land, RTR = reduced-tilled transplanted rice on flat land, CT = conventional tillage.

can obviate the problem of N losses and still be "water-wise." Increased availability of P under submerged soil conditions has been known to increase rice productivity. Intermittent ponding expectedly influences the bio-geochemical cycles that might shape events that follow soil drying and rewetting in the bed-planting system. We have observed that the raised bed remains moist for a long time with little soil cracking and a lot of earthworm activity during the rice season (Chaudhary et al 2002). Soil cracking is quite prevalent in puddled soils. The process of drying and rapidly rewetting the soil has been shown to increase the amount of water-soluble phosphorus predominantly released from the soil microbial biomass. This significantly affects phosphorus availability and might also influence results from analyses involving soil tests based on extraction of dried soils, already an enigma for the correct evaluation of P availability in rice soils.

Management of crop residues and planting into loose soils avoid burning and subsequent air pollution. This also helps to overcome organic matter decline and nutrient depletion and promotes groundwater recharge. A strategy of incorporating the silica-rich rice residues seems inevitable in acidic soils of the eastern Gangetic Plains to solve the liming problem. Liming of these soils reportedly has improved the yields of wheat and other upland crops. Incorporation of silica-rich rice residues into isoelectric soils increases the negative charge and improves the base saturation of the exchange complex and reduces fixation of applied P. Although incorporation of silica-rich organic fertilizer is widely practiced in the hills, it also needs more rigorous testing for its effects on physico-chemical properties of acidic soils that are commonly found in the subhumid and humid eastern Gangetic Plains. In farmer participatory trials conducted in western Uttar Pradesh, zero-tilled wheat, when mulched with residues of the previous rice crop, not only improved the wheat yield but also saved irrigation time and reduced the weed population (Table 9). There is also the subject of planting crops into loose residues since existing equipment for zero-tillage and bed planting is based on inverted-T openers that rake the loose straw into piles that create problems for planting. Engineers and local manufacturers are now working together in the RWC to solve this problem so that residues can be kept as mulch on the soil surface and provide better surface-soil physical and biological properties, improve

Table 9. Effects of crop residues on yield of zero-till planted wheat and savings in irrigation time in farmer participatory trials in Ghaziabad and Meerut districts, Uttar Pradesh, India.

Treatment	No. of plants m^{-2}	No. of weeds m^{-2}	Irrigation time (h)	Yield (t ha^{-1})
Manually harvested rice followed by zero-till wheat	133	30	43	5.7
Partial residue burning followed by zero-till wheat	132	30	46	5.8
Zero-till planted mulched wheat in combine-harvested rice	129	21	40	6.0
Convential-tillage farmer practice	117	54	64	5.2

infiltration and water-use efficiency, plant stands, and yields, and provide an alternative to burning.

Conclusions

The rice-wheat system of the IGP is a major system for maintaining food security for this populous region and providing employment and income for the region's farmers. This paper has outlined various resource-conserving technologies that are being promoted by the RWC in the region that lead to higher yields at less cost, improve natural resource efficiency, and have significant environmental benefits, especially in regard to greenhouse gas emissions. For increasing water productivity, these new RCTs can make significant contributions. Zero-till, permanent bed-planting systems and new nonpuddled rice establishment techniques coupled with laser land leveling can go a long way to increasing the use efficiency of this vital natural resource. Water is and will continue to be a major limiting factor for agricultural production as competition for its use from domestic and industrial uses rises in the next decade. This makes it even more urgent that the RCTs promoted in this paper become adopted in the IGP.

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Crop-water relations in rice-wheat cropping under different tillage systems and water-management practices in a marginally sodic, medium-textured soil

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Management of resources and sustainability of the rice-wheat cropping system have become a matter of concern in South Asia, especially where water is increasingly scarce. New soil and water management technologies, such as aerobic cultivation of rice on raised beds or on flat nonpuddled land, and zero-tillage in wheat, are rapidly emerging. This paper reports on a field experiment carried out at Modipuram, Uttar Pradesh, India, to study some of these new technologies. Rice (Pro-agro 6111) was direct-seeded on raised beds and on flat land and grown under two aerobic water regimes: (1) irrigation was applied when the soil water tension at 15-cm depth reached 10 kPa or (2) when it reached 20 kPa. The control was continuously flooded transplanted rice. Wheat (BPW 343) was sown after rice using five tillage practices: conventional tillage, zero-tillage with or without controlled traffic, zero-tillage with paired-row planting, and bed-planting (same beds as used for rice). Flooded transplanted rice and conventionally tilled wheat gave the highest yields. With irrigation at 10 or 20 kPa soil water tension, bed-planted rice reduced water input by 45–51% but lowered yield by 52–53% compared with transplanted rice, whereas dry-seeded rice on flat land reduced water input by 51–57% and lowered yield by 36–46%. Zero-tilled wheat with controlled traffic gave yields similar to those of conventional wheat and had the same water use. More study is needed to understand the effect of aerobic rice on flat land or on raised beds, and of wheat under zero-tillage, on soil properties, crop productivity, and water use.

Irrigated agriculture is the biggest consumer of water worldwide, and rice is the major beneficiary of irrigation in Asia (Barker et al 1999). Rice-wheat is an important cropping system in South Asia (Timsina and Connor 2001). Rice is commonly cultivated as a transplanted crop in flooded, puddled soil. Mainly because of the continuous seepage and percolation, the evaporation from the water layer and the amount of water used in wet-land preparation, the water requirement of rice at the field level is relatively high compared with that of other cereal crops (Bouman 2001, Tuong 1999). Lately, the increased demand for water by agriculture and other sectors of society (cities, industry) has adversely affected its quality and availability (Gleick 1993, Postel 1997). For example, in parts of Punjab and Haryana in India, where irrigation is provided by pumping groundwater, water tables have dropped by 0.1–1.0 m y^{-1} in the past decade, thereby increasing the scarcity and cost of irrigation water (Gill 1994, Harrington et al 1993, Sharma et al 1994, Sondhi et al 1994). In the central and southern districts of Haryana, where most of the area is irrigated using gravity (canal) water, a fast increase in the groundwater table by 0.3–0.4 m y^{-1} has been observed, leading to problems of waterlogging and salinization (Sharma et al 1994). In view of the projected increase in rice production required to feed a still-growing population in Asia (Hossain 1997, IRRI 1997), an efficient use of water in rice ecosystems is of critical importance. To sustain the rice-wheat cropping system, technologies need to be developed that decrease the water use but increase the water productivity of rice and wheat.

Rice can withstand a soil water tension of 10 to 15 kPa, which may arrive in 2–4 days after the disappearance of ponded water from the field, without a significant decline in grain yield (Sharma 1989). This characteristic offers an opportunity to cultivate rice as an upland crop in nonpuddled soil with strict irrigation schedules. Such a system of rice cultivation has been termed “aerobic rice” (Bouman 2001, Wang Huaqi et al, this volume). Aerobic rice can be grown on raised beds spaced between furrows to channel irrigation water onto the field. Raised-bed systems are being pioneered in the Indo-Gangetic Plains of India (Gupta et al, this volume). Wheat growth in postrice soils may be constrained because of changes in soil physical properties caused by puddling for rice cultivation. Poor soil tilth, restricted drainage, and inadequate soil aeration are some of the major limitations for wheat to express its yield potential in postrice soils (Timsina and Connor 2001). Changes in methods of crop establishment that maintain soil structure, such as zero/conservation tillage and raised-bed cultivation, may have positive effects on total system productivity and water-use efficiency. However, in-depth study is required on nutrient and water management to maximize total system productivity. In 2001, a field study was undertaken at Modipuram, India, to investigate the effects of different tillage systems and water regimes on the yield and water-use efficiency of rice and wheat. This paper reports the findings of the first year of experimentation.

Materials and methods

The field experiment was undertaken at the experimental farm at Modipuram of the Sardar Vallabhbhai Patel University of Agriculture and Technology (29°01′N, 77°45′E). The climate in the area is semiarid, with an average annual rainfall of 800 mm, minimum temperature of 0–4 °C in January, maximum temperature of 41 °C in June, and relative humidity of 67–83% throughout the year. The experimental soil is a marginally sodic silt loam, with low salt content and poor structural development. Chemical and physical properties are summarized in Table 1. The surface soil is medium in organic carbon, low in available N, high in Olsen P, and medium in 1 N NH_4OAc-extractable K. The DTPA-extractable Zn, Cu, Fe, and Mn in the topsoil are in the high range.

Table 1. Chemical and physical soil properties at the experimental site.

Chemical properties

Soil depth (cm)	OC[a] (%)	pH (1:2 ratio)	EC[b] (dS m^{-1})	Available nutrients (kg ha^{-1})			DTPA-extractable nutrients (ppm)			
				N	P	K	Zn	Cu	Fe	Mn
0–15	0.5	8.1	0.4	194	45	295	2.3	2.5	8.2	4.5
15–30	0.3	8.3	0.3	166	5	218	0.8	1.6	5.6	5.6
30–45	0.2	8.5	0.4	161	5	224	0.5	1.0	4.4	5.7
45–60	0.2	8.7	0.3	160	9	248	0.5	1.2	3.6	8.6

[a]OC = organic carbon. [b]EC = electrical conductivity.

Physical properties

Soil depth (cm)	Particle size distribution (%)			Texture class (ISSS)[a]	Particle density (Mg m^{-3})	Bulk density (Mg m^{-3})	MWD[b] (mm)	Water retention (%)		AWC[c] (%)
	Clay	Silt	Sand					30 kPa	1,500 kPa	
0–15	19	26	55	Silty loam	2.65	1.41	0.71	18	7	12
15–30	24	27	49	Silty loam	2.63	1.64	0.68	19	9	9
30–45	26	23	51	Silty loam	2.64	1.59	0.69	19	9	9
45–60	31	26	43	Silty clay loam	2.65	1.61	0.72	18	11	8

[a]ISSS = International Soil Survey System. [b]MWD = mean weight diameter of soil aggregates. [c]AWC = available water content.

Rice

Rice was seeded in rows on flat land (DSR) and on raised beds (BPR) with a width of 37 cm. The furrows between the beds had a width of 30 cm. The row spacing was 20 cm in DSR and 20 cm on the beds and 47 cm across the furrows in BPR. In both BPR and DSR, the crop was grown under two water regimes: (1) irrigation was applied when the soil water tension at 15-cm depth reached 10 kPa or (2) when it reached 20 kPa. In an additional treatment ($DSR_{20\text{-}47\text{-}20}$), rice was row-seeded on flat land with the same spacing as in BPR, that is, 20-47-20 cm, and irrigated at 10-kPa soil water tension. The control was continuously flooded transplanted rice (TPR). Two cultivars, Pro-agro 6111 (hybrid) and PR 106 (inbred), were grown in plots of 20 × 12 m, arranged in a complete random block design with four replications. BPR and DSR were sown on 12 June, on the same day as the nursery was established for TPR. Transplanting of TPR was done on 1 July using 19-d-old seedlings, with one seedling hill^{-1}. BPR and DSR received basal applications of 30 kg P ha^{-1}, 60 kg K ha^{-1}, 25 kg $ZnSO_4$ ha^{-1}, and 50 kg $FeSO_4$ ha^{-1}. The first dose of N was applied at 18 days after sowing (DAS) at 50 kg ha^{-1}. The sources of N, P, and K were urea, single superphosphate, and muriate of potash, respectively. In the early growth stages, visual symptoms of Fe or Zn deficiency were observed and additional Fe and Zn were applied by foliar spraying. TPR received the same amounts of basal fertilizer (P, K, Zn, and Fe) as BPR and DSR, plus 50 kg N ha^{-1} basal. In all treatments, subsequent N doses were applied (topdressed) when leaf color chart (LCC) readings were below 4 in hybrid rice and below 3 in inbred rice. The crop was harvested on 29 September. At harvest, plant height, panicles m^{-2}, grains panicle^{-1}, 1,000-grain weight, spikelet sterility, and grain and straw weight were measured. The grain weight was corrected to 15% moisture content.

The bulk density of the soil was determined from core-ring samples taken at 15-cm depth intervals at seeding/transplanting. Percolation rates were determined in three replications using 20-cm-diameter and 30-cm-long PVC pipes pushed 15 cm deep into the soil. Percolation rates were also determined at different soil depths by sequential removal of 5-cm soil layers starting from the surface. The soil water tension was measured at 15-cm depth in BPR and DSR in three replications using mercury tensiometers. In BPR, tensiometers were placed in the middle of the beds. Irrigation was applied using PVC pipes of 10-cm diameter and the amount of water applied to each plot was measured using a fixed water meter. Weather data were collected from a meteorological station about 1 km away from the site. The total water use was computed as the sum of irrigation and rainfall, and the water-use efficiency as the ratio of grain yield over total water use. The evapotranspiration (ET) was calculated from the weather data using the modified Penman equation (e.g., Allen et al 1998). The seasonal seepage and percolation loss was calculated by subtracting the calculated ET from the measured total water input (ignoring any change in soil water content).

Wheat

Wheat (BPW 343) was sown after rice using five tillage systems: conventional tillage (CT; the land was prepared with two passes of the cultivator plus one planking, and wheat was sown with a seed drill at 20-cm row spacing), zero-tillage (ZT; wheat was sown with a seed drill at 20-cm spacing without land preparation), zero-tillage with controlled traffic (ZT_{ct}; same as ZT but skipping every 8th row so that the soil under the wheels of the tractor remained unsown [so-called "tramlines"]), zero-tillage with paired-row planting (ZT_{pr}; same as ZT_{ct} except that 8 rows of wheat were sown in pairs spaced 10 cm apart between two wheels of the tractor), and raised beds (BPW; wheat was sown on the same raised beds as the previous rice crop using a bed planter; the beds were reshaped with the sowing of wheat). Glyphosate was sprayed at 3 L ha^{-1} about 2 weeks before sowing to kill weeds in all ZT and BPW plots.

All plots received 26 kg P ha^{-1} (as single superphosphate) and 50 kg K ha^{-1} (as muriate of potash) at sowing. Nitrogen was applied as urea at 120 kg N ha^{-1} in all CT and ZT plots, of which 50% was applied at the time of sowing, 25% at 47 DAS, and 25% at 72 DAS. The N in the BPW plots was managed in two ways: in one set of plots (BPW_N), 100% N was applied as basal, whereas, in the other set (BPW), 60 kg N ha^{-1} was applied as basal and the remainder according to SPAD (chlorophyll meter) readings (30 kg ha^{-1} per application). In BPW, basal N was placed at 10-cm depth between two rows of wheat using the bed planter. The N topdressings in the BPW plots were made when the SPAD values were the same as in the CT treatment at the time of their split applications of N (at 47 and 72 DAS).

All plots received 60 mm of irrigation water before sowing. The CT and ZT plots received irrigation at all critical growth stages of the crop: at about 2 weeks after emergence, active tillering, late jointing, flowering, and milky stage. Irrigation in the BPW plots was applied when the soil water tension at 20-cm depth increased to 50 kPa. The first irrigation was provided at 16 DAS in all ZT and BPW plots and at 21 DAS in the CT plots. An irrigation of 52 mm was provided on 27 March 2002 (24 days before harvest) to all plots.

The soil water tension at 15-cm depth was recorded daily in all treatments in three replications using mercury tensiometers. Air-filled porosity of the soil was determined at 0–7.5- and 7.5–15-cm depths after irrigation at 45 DAS in CT and ZT and at 51 DAS in BPW. Soil pH (1:2 soil:water ratio) at 1-cm depth increments down to 15-cm depth was recorded in all plots at flowering.

The crop was harvested on 21 April 2002. Data on crop yield and yield components were recorded. Total water use and water-use efficiency were computed as for rice.

Results and discussion

Rice

Variety PR 106 failed completely because of severe brown spot disease. Hence, only data on Pro-agro 6111 are presented. A total of 360 mm of rainfall was received during the crop growth period (from 12 June to 29 September 2001). No rainfall occurred after 13 September. The minimum air temperature varied from 21 to 29 °C, the maximum air temperature from 28 to 40 °C, and the relative humidity from 49% to 100%.

Percolation. The average percolation rate over the whole season in TPR, BPR, and DSR was 12, 20, and 30 mm d^{-1}, respectively. The subsoil (below 20-cm depth) had higher permeability than the topsoil (Table 2). The 15–20-cm soil layer appeared to limit percolation. The relatively high bulk density (Table 1) and high concentration of sodium in the soil may have been responsible for the relatively low seasonal-average percolation rates. When irrigated, sodium gets hydrated and seals the pore spaces, thereby lowering the permeability of the soil.

Water use and soil water regime. The TPR plots were kept continuously submerged. Other plots were irrigated uniformly up to 20 DAS, after which the irrigation treatments were planned to start. However, the bed-planted rice (BPR) suffered badly (from drought and Zn and Fe deficiency) at the seedling stage, even at only 10 kPa soil water tension at 15-cm depth. Therefore, all BPR plots were irrigated daily for 2 weeks from 34 DAS onward. To keep uniformity in the water treatments, all DSR plots were also irrigated daily for 2 weeks from 37 DAS onward. The planned irrigation schedules were resumed at 51 DAS for all treatments. Irrigation was stopped 7 days before the rice crop reached its physiological maturity. Total water use and the components of the field water balance for the different treatments are given in Table 3. A total of 3,880 mm of irrigation water was applied in TPR vis-à-vis 1,990 mm in BPR_{10kPa}, 1,710 mm in BPR_{20kPa}, 1,720 mm in DSR_{10kPa}, 1,450 mm in DSR_{20kPa}, and

Table 2. Percolation rate (mm d^{-1}) at different soil depths.

Soil depth	Percolation rate
Surface	32
5 cm	31
10 cm	43
15 cm	42
20 cm	60

Table 3. Components of the water balance in rice.

Treatment[a]	Total water use[b] (mm)	Evapotranspiration (mm)	Seepage and percolation (mm)
TPR	4,240	1,020	3,220
BPR_{10kPa}	2,350	760	1,590
BPR_{20kPa}	2,070	670	1,400
DSR_{10kPa}	2,080	760	1,320
DSR_{20kPa}	1,810	670	1,140
$DSR_{20\text{-}47\text{-}20}$	2,080	760	1,320

[a]See text for explanation. [b]Irrigation plus rainfall.

1,720 mm in $DSR_{20-47-20}$. The total water use, including 360 mm of rainfall, in TPR was about double that in BPR and DSR. Of the total water use, about 76%, 68%, and 63% was estimated to be lost as seepage and percolation in TPR, BPR, and DSR, respectively.

The soil water tension at 15-cm depth varied from 2 to 10 kPa in the BPR_{10kPa}, DSR_{10kPa}, and $DSR_{20-47-20}$ plots and from 4 to 25 kPa in the BPR_{20kPa} and DSR_{20kPa} plots (Fig. 1). The soil water tension at 40-cm depth was always below 8 kPa in all plots (data not shown).

Yield and water-use efficiency. Rice yield and yield components were affected by establishment method and irrigation level (Table 4). Grain and straw yields were

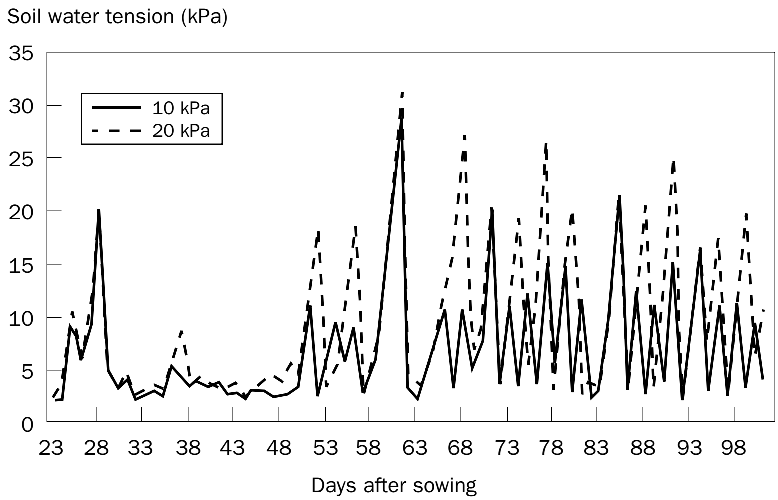

Fig. 1. Mean soil water tension at 15-cm depth in time in direct-seeded rice on flat land (DSR) and on raised beds (BPR) under two irrigation water treatments: irrigation at 10 kPa and at 20 kPa tension.

Table 4. Yield, yield components, and water-use efficiency of rice.

Treatment[a]	Grain yield[b] (t ha^{-1})	Straw yield (t ha^{-1})	Panicles m^{-2}	Spikelets $panicle^{-1}$	1,000-grain weight (g)	Spikelet sterility (%)	Water-use efficiency (g grain kg^{-1} water)
TPR	10.29 a	6.52 a	286 a	192 a	24.6 a	17 a	0.24
BPR_{10kPa}	4.96 c	3.49 c	269 a	113 b	23.1 b	17 a	0.21
BPR_{20kPa}	4.81 c	3.34 c	262 a	117 b	22.6 b	18 a	0.23
DSR_{10kPa}	6.53 b	4.70 b	295 a	116 b	23.3 b	15 a	0.31
DSR_{20kPa}	5.60 c	3.89 c	287 a	113 b	23.1 b	14 a	0.31
$DSR_{20-47-20}$	4.73 c	3.35 c	236 a	110 b	23.3 b	15 a	0.23

[a]See text for explanation. [b]Means in a column followed by a common letter are not significantly different at the 5% level.

highest in TPR, followed by DSR_{10kPa}. The extremely high grain yield (and, consequently high harvest index) of TPR could not be explained (measured data were checked carefully). The yield was statistically the same in BPR_{10kPa}, BPR_{20kPa}, DSR_{20kPa}, and $DSR_{20\text{-}47\text{-}20}$. The TPR had the tallest plants, more spikelets per panicle, and a higher 1,000-grain weight. The number of effective tillers m^{-2} and spikelet sterility were comparable in different treatments. Water-use efficiency was highest in DSR, followed by TPR and BPR.

Wheat

Air-filled porosity. Air-filled porosity at 0–7.5- and 7.5–15-cm depth was always highest in BPW, followed by CT and ZT (Fig. 2). A value of 10% is considered critical for most cereal crops. At 0–7.5-cm depth, this value was achieved within a few hours after irrigation in BPW, whereas it took about 4–7 days after irrigation in CT and ZT. At 7.5–15-cm depth, 10% air-filled porosity was reached in about 1 day after irrigation in BPW and in about 5 days after irrigation in CT and ZT. Thus, aeration was relatively more favorable for wheat cultivation in BPW than in CT and ZT.

Water use and soil water regime. Seven irrigations were applied to CT and ZT and 8 to BPW, including the presowing and common irrigation on 27 March (Table

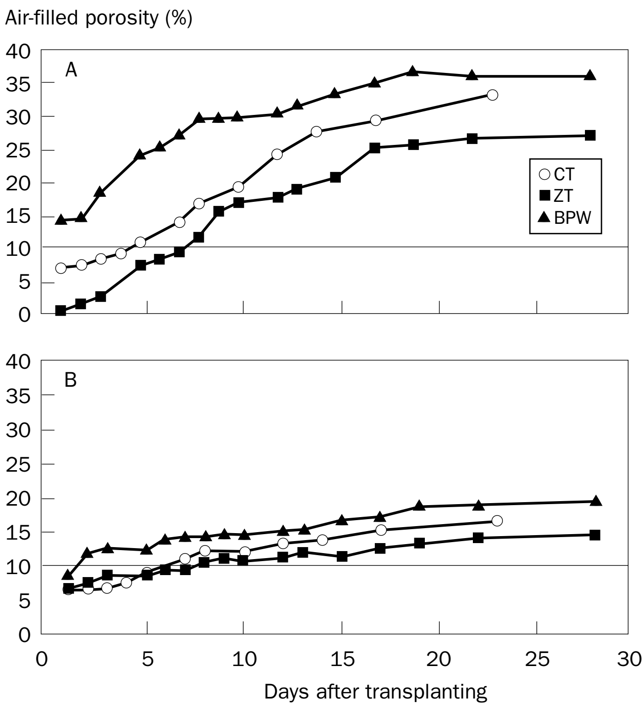

Fig. 2. Air-filled porosity in time at 0–7.5-cm depth (A) and at 7.5–15-cm depth (B) in wheat under conventional tillage (CT), zero-tillage (ZT), and on raised beds (BPW).

Table 5. Amount (mm) of irrigation water applications in wheat.

Date	Days after sowing	Treatment		
		CT[a]	ZT[b]	BPW[c]
5 Dec 2001	16	–	60	48
10 Dec 2001	21	52	–	–
3 Jan 2002	45	52	50	40
25 Jan 2002	67	–	–	40
31 Jan 2002	73	52	50	–
7 Feb 2002	80	–	–	40
28 Feb 2002	101	–	–	40
1 Mar 2002	102	52	50	–
14 Mar 2002	115	–	–	40
15 Mar 2002	116	60	60	–
27 Mar 2002	128	52	52	52
Total		320	322	300

[a]CT = conventional tillage. [b]ZT = zero-tillage. [c]BPW = bed-planted wheat.

5). The total water use, including 80 mm of rainfall, was 348, 350, and 328 mm in CT, ZT, and BPW, respectively. The soil water tension at 20-cm depth varied from 2 to more than 80 kPa in CT and ZT, and from 3 to 72 kPa in BPW (Fig. 3).

N applications. The SPAD values are shown in Table 6. Split applications of N were made on 5 and 30 January in CT and ZT and on 7 February in BPW. Thus, CT, ZT, and BPW_N plots received a total of 120 kg N ha^{-1}, whereas BPW received 90 kg N ha^{-1}.

Yield and water-use efficiency. The grain yield of wheat was highest in CT and ZT_{ct}, whereas the numbers of grains per spike and the 1,000-grain weight were highest in BPW_N (Table 7). The number of spikes per unit area correlated best with yield; it was highest in CT and ZT. Better soil aeration and soil water regimes probably favored higher grain weight and more grains per spike in BPW. Tillering was also better in BPW, but it could not compensate for the roughly 40% area loss because the furrows between the beds were left unsown. The water-use efficiency was highest in CT, followed by ZT_{ct}. BPW_N saved about 20–22 mm (6%) of irrigation water over ZT and CT, but yielded 18% less than CT and 16% less than ZT_{ct}.

Soil reaction. The mean pH in the top 15-cm soil layer was highest in BPW (8.3–8.5), followed by ZT (7.9–8.1) and CT (7.5–7.9) (Fig. 4). The trends in pH were associated with the different hydrodynamics in the different treatments. In wheat, the CT treatment was imposed in plots that were puddled (TPR) in the preceding rice crop. These puddled plots were continuously flooded and had a continuous downward flow (percolation) of water that prevented the accumulation of salt (sodium) in the surface layer. On the other hand, the ZT treatment in wheat was imposed in plots under "aerobic" conditions in the direct-seeded treatments of the preceding rice crop (DSR). In DSR, water fluxes are in both a downward (during irrigation) and upward (during the drying phase) direction, which favors the accumulation of salts. The beds

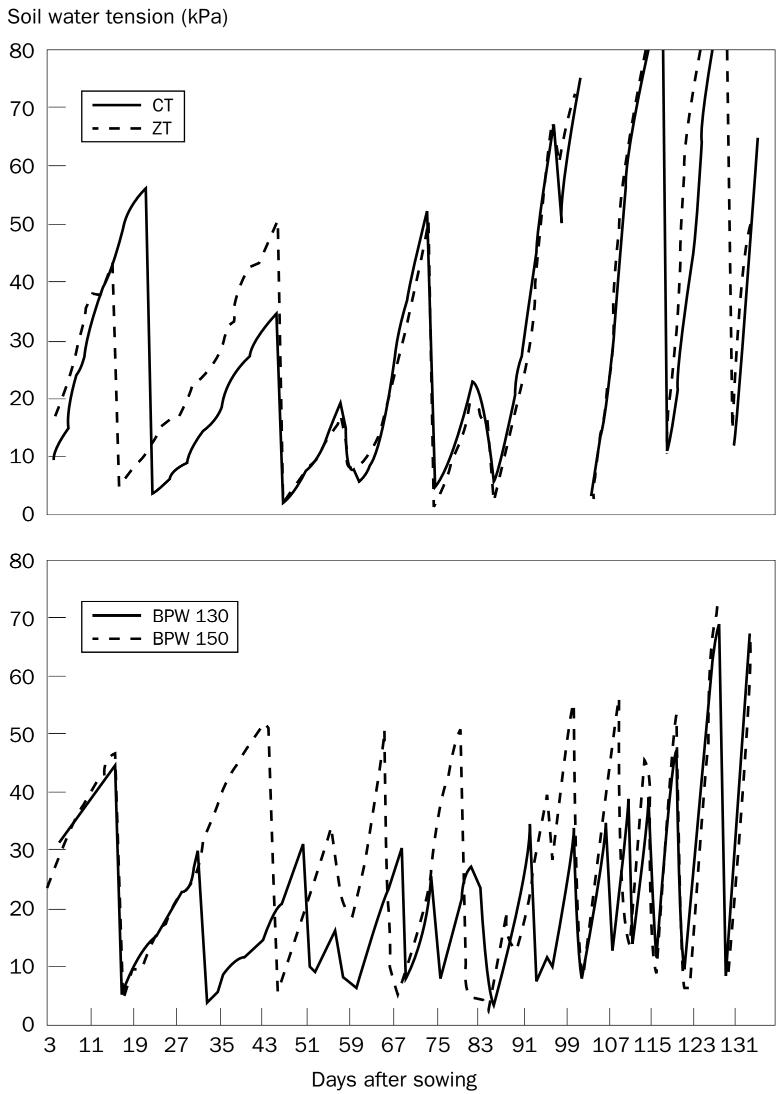

Fig. 3. Mean soil water tension at 15-cm depth in time in wheat under conventional tillage (CT), zero-tillage (ZT), and on raised beds with 100% of the N applied as basal (BPW I30) and with N applied according to SPAD readings (BPW I50).

Table 6. SPAD (chlorophyll meter) values measured on different dates in wheat.

Date	Treatment			
	CT[a]	ZT[b]	BPW[c]	BPW_N[d]
5 Jan 2002	38.1	38.1	42.6	45.0
9 Jan 2002	42.2	43.9	44.8	47.6
17 Jan 2002	43.6	43.7	45.1	48.3
23 Jan 2002	39.9	41.2	43.9	45.9
30 Jan 2002	38.6	39.5	41.5	45.7
6 Feb 2002	39.3	38.1	38.8	42.6
13 Feb 2002	46.0	41.5	41.0	43.1
20 Feb 2002	43.3	43.0	45.4	42.8
27 Feb 2002	41.6	41.6	44.3	42.1
6 Mar 2002	40.0	41.2	44.2	44.3
13 Mar 2002	39.1	38.8	40.6	39.5
23 Mar 2002	38.3	36.6	38.7	39.3

[a]CT = conventional tillage. [b]ZT = zero-tillage. [c]BPW = bed-planted wheat, N applied according to SPAD readings. [d]BPW_N = bed-planted wheat, 100% N applied as basal.

Table 7. Yield, yield components, and water-use efficiency of wheat.

Treatment[a]	Grain yield[b] (t ha^{-1})	Straw yield (t ha^{-1})	Panicles m^{-2}	Grains $spike^{-1}$	1,000-grain weight (g)	Water-use efficiency (g grain kg^{-1} water)
CT	5.39 a	5.43 a	329 a	40 abc	41 ab	1.55
ZT	5.08 ab	5.34 a	337 a	39 bc	41 ab	1.45
ZT_{ct}	5.29 a	5.50 a	347 a	39 bc	40 b	1.51
ZT_{pr}	4.79 bc	5.03 ab	335 A	38 c	40 b	1.37
BPW	4.27 d	4.72 b	272 b	42 ab	41 ab	1.30
BPW_N	4.42 cd	4.67 b	266 b	43 a	41 ab	1.35

[a]See text for explanation. [b]Means in a column followed by a common letter are not significantly different at the 5% level.

in wheat (BPW) were the same as in the previous rice crop (BPR), in which water fluxes are always in the upward direction (except during rainfall events). This favors the accumulation of salts in the surface layer.

Conclusions

Puddled transplanted rice (TPR) and conventionally tilled wheat (CT) gave the highest yields in our marginally sodic medium-textured soil. With irrigation at 10 and 20 kPa soil water tension, bed-planted rice (BPR) saved 45–51% water but lowered grain yield by 52–53% compared with TPR, whereas dry-seeded rice on flat land (DSR)

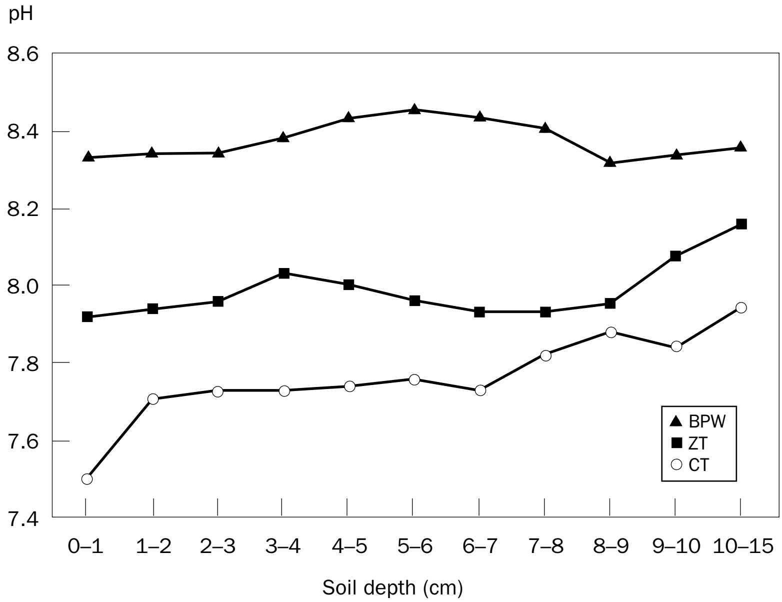

Fig. 4. Mean soil pH in the 0–15-cm topsoil in wheat under conventional tillage (CT), zero-tillage (ZT), and on raised beds (BPW).

saved 51–57% water and lowered yield by 36–46%. Despite the basal fertilizer-Fe and -Zn applications, visual symptoms of Fe or Zn deficiency were noted in the direct-seeded plots (BPR, DSR). In wheat, zero-tillage with controlled traffic (ZT_{ct}) gave a similar yield and used the same amount of water as CT. BPW_N saved about 20–22 mm (6%) of irrigation water, but yielded about 16–18% less than CT and ZT_{ct}.

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Effects of rice establishment methods on crop performance, water use, and mineral nitrogen

A.K. Singh, B.U. Choudhury, and B.A.M. Bouman

To mitigate the increasing water scarcity in Asia, new ways of growing rice need to be developed that use less water than conventional lowland rice. An experiment was conducted in New Delhi, India, to evaluate the yield and water use of rice established by different methods: transplanting, wet seeding, and dry seeding with subsequent aerobic soil conditions on flat land and on raised beds. Transplanted rice yielded 5.5 t ha^{-1} and used 360 mm of water for wet-land preparation and 1,608 mm during crop growth. Compared with transplanted rice, dry-seeded rice on flat land and on raised beds reduced total water input during crop growth by 35–42% when the soil was kept near saturation, and by 47% and 51% when the soil dried out to 20 and 40 kPa moisture tension in the root zone, respectively. Most of the water savings were caused by reduced percolation losses. Moreover, no irrigation water was used during land preparation. However, the dry seeding of rice reduced yield by 23–41% on flat land and by 41–54% on raised beds compared with transplanted rice. There were no large differences in water productivity among treatments. In the topsoil, nitrogen occurred relatively more as ammonium under flooded transplanted and flooded wet-seeded conditions and as nitrate under dry-seeded aerobic conditions. The dry seeding and subsequent aerobic growing of rice face several potential yield-reducing factors that need to be studied further: micronutrient deficiency (iron), nematode and weed infestation, and proper cultivar development. When grown on raised beds, the variety needs to be able to compensate for the loss in cropped area (caused by the relatively large row spacing between the beds) by producing more productive tillers.

Rice is the staple food in Asia, the most populous continent, which accounts for almost 90% of the global production and consumption (IRRI 1997). The demand for rice in Asia is likely to keep increasing because of the still-increasing population. Asia produces about 530 million tons of rice every year and more than 75% of this comes from irrigated land (IRRI 1997). Irrigated rice requires a lot of water: about 3,000–5,000 L are used to produce 1 kg of grain (IRRI 2001). Because of this high water requirement, the increasing water shortage in Asia threatens the sustainability of the irrigated rice system (Tuong and Bouman 2002). Water requirements for rice are high because rice is generally grown under "lowland" conditions: the soil is puddled (wet-land preparation to create a muddy layer) and, after the transplanting of rice seedlings, the field is kept flooded with up to 5–10 cm of water until some 10 days before harvest. In loamy soil, about 60–70% of the total amount of water applied is lost through deep percolation and seepage, and only a small portion (30–40%) is used consumptively by evapotranspiration (Koga 1992). Moreover, the puddling of rice fields requires about 150–750 mm of water (Bouman 2001).

To mitigate the increasing water scarcity in Asia, it is imperative to develop new ways of growing rice that use less water while maintaining high yields. Recent research suggests several possibilities based on different establishment techniques, such as direct wet seeding (Tabbal et al 2002) and direct dry seeding, either on flat land or on raised beds (Borrell et al 1997, Hobbs and Gupta 2002). Wet seeding is becoming more and more popular in the irrigated areas of Thailand, Malaysia, Vietnam, and the Philippines (Pandey and Velasco 1999, Sattar 1992). Dry seeding can substantially reduce the water demands in rice by avoiding wet-land preparation. If, after sowing, the field is not flooded, then rice grows "aerobically" like an upland crop and uses considerably less water than flooded lowland rice (Wang Huaqi et al and Yang Xiaoguang et al, this volume). Dry seeding can be done on raised beds, which may increase the overall resource-use efficiency (Hobbs and Gupta 2002). Also, dry-seeded rice offers scope to advance crop establishment and to increase the effective use of early season rainfall (Tuong 1999). All these water-saving technologies result in a shift from purely anaerobic to (partially) aerobic conditions. This shift may lead to unknown challenges with respect to productivity, weed infestation, availability of nitrogen (N) and micronutrients, and pest and disease incidence, and requires thorough investigation before these technologies are recommended to farmers. In this paper, preliminary results of a field experiment conducted with the following objectives are presented:

1. To compare the yield, water use, water productivity, and components of the water balance of rice established by different methods: transplanting, wet seeding, and dry seeding on flat land and on raised beds. The dry-seeded rice is grown aerobically.
2. To compare the availability of mineral N in the soil under the above establishment methods.
3. To study yield-limiting factors under increased aerobic conditions.

Materials and methods

Experiment description

The experiment was conducted in the wet season of 2001 at the research farm of the Indian Agricultural Research Institute (IARI), New Delhi, India (28°36′N, 77°12′E). The soil was classified as a Typic Ustochrept with average sand, silt, and clay contents in the 0–20-cm topsoil of 52%, 36%, and 12%, respectively. The available N content was low (129 kg ha^{-1}), whereas available P (12 kg ha^{-1}) and K (146 kg ha^{-1}) contents in the 0–20-cm layers were in the medium range. The average saturated hydraulic conductivity down to a depth of 60 cm was 0.51 cm h^{-1}. The water held by the soil at –10 kPa (pF 2) and at –1,500 kPa (pF 4.2) matrix potential was 28% and 6% by weight, respectively (0–20-cm depth). The groundwater table was more than 3 m below the soil surface throughout the crop season.

The experiment consisted of two puddled treatments and five nonpuddled treatments. To avoid lateral water flow from the flooded, puddled plots to the aerobic nonpuddled plots, the puddled plots were grouped together and separated from the nonpuddled plots by a bare strip 2 m wide. The puddled and nonpuddled treatments were laid out in a randomized block design with four replicates in bunded plots of 10 × 7 m. The treatments were

- TPR: transplanted puddled rice (hill spacing 20 × 20 cm).
- WSR: wet-seeded puddled rice (row spacing 20 cm).
- DSR: dry-seeded rice (row spacing 20 cm).
- FB: dry-seeded rice on "flat beds" (using row spacing as in the raised beds: 2 rows spaced 20 cm apart, then 47 cm till the next 2 rows).
- RB_{00}: dry-seeded rice on raised beds (raised bed width 37 cm; furrow width 30 cm; row spacing on the beds 20 cm, with 47 cm between the paired rows on the beds); irrigated to keep the soil in the furrows between saturation and field capacity.
- RB_{20}: same as RB_{00} but irrigated when the soil water tension at 20-cm depth in the center of the beds reached 20 kPa.
- RB_{40}: same as RB_{00} but irrigated when the soil water tension at 20-cm depth in the center of the beds reached 40 kPa.

Standing water of 5 ± 2-cm depth was maintained only in the TPR and WSR treatments. In the DSR and FB treatments, plots were irrigated as frequently as required to maintain near-saturated soil conditions. In the raised-bed treatments, irrigation water was applied in the furrows. Rice variety Pusa-44 was seeded manually (using pregerminated seeds) in WSR, DSR, and FB and sown mechanically by a bed planter (manufactured by the Pantnagar University of Agriculture and Technology) in the raised-bed treatments on 5 July 2001. In TPR, 3-week-old rice seedlings were transplanted on 21 July 2001. Fertilizer P and K were applied basally at 30 and 60 kg ha^{-1}, respectively. Nitrogen was applied at 120 kg ha^{-1} in three splits: 50% basal, 25% at maximum tillering, and 25% at flowering. Zinc (Zn) was applied as $ZnSO_4$ and iron (Fe) as $FeSO_4$ in a basal dose of 25 and 50 kg ha^{-1}, respectively. Iron deficiency was observed in the initial stages of crop growth in the raised beds and 1% $FeSO_4$ was applied twice weekly from 3 weeks after germination till maximum tillering. The crops were harvested on 7, 14, 14, 20, and 20 November for TPR, WSR, DSR, RB, and FB, respectively.

Measurements

At the start and end of the experiment, soil samples were collected for measuring the soil moisture content in the root zone. In the raised-bed treatments, the soil matrix potential was monitored daily at 20- and 40-cm depth in the center of the beds using mercury tensiometers. In all plots, irrigation water was applied through flexible hoses and measured using a flow meter. Percolation rates were measured on a daily basis by recording the depth of water in plastic cylinders of 45-cm length (15 cm kept above the soil surface). The cylinders were kept closed at the top to prevent evaporation loss. The water level in the cylinders was kept at the same level as the surrounding ponded water depth in the plots by frequent refilling. In the raised beds, the cylinders were installed in the furrows. In all treatments, the soil ammonium (NH_4^+) and nitrate (NO_3^-) N contents were measured before emergence and at flowering in the top 60 cm of soil in four layers of 15-cm depth. DTPA (diethylene-triamine-pentaacetic acid) extractable Fe (1:2 soil water ratio) was measured in the raised beds at 0–15- and 15–30-cm depth around maximum tillering. Nematode occurrence was monitored by measuring the population densities of juveniles in the soil at the beginning of the experiment and by scoring visually observed root galling during grain filling and at harvest on a 0–5 root-knot index. Final yield was harvested from a 6-m^2 area and grain yield recorded at 14% moisture content. Daily weather, including rainfall, was obtained from the meteorological observatory at the IARI farm.

Calculations

The water balance of a rice field is

$$\delta W = I + R - P - ET - R_{off} \quad (1)$$

where δW = change in soil water storage, I = irrigation, R = rainfall, P = (deep) percolation, ET = evapotranspiration, and R_{off} = runoff (all expressed in mm water). In our experiment, I, R, and P were measured directly. R_{off} was assumed to be zero because the plots were bunded (30 cm height) and no bund overflow occurred. The change in soil water stored in the root zone was calculated from the measured soil water contents at the start and end of the experiment. ET was estimated as the residual of the water balance (equation 1).

Water productivity was calculated as the weight of grains produced per unit water used (g grain kg^{-1} water). The following values were computed:

- WP_{ET}: grain weight per unit water evapotranspired.
- WP_{IR}: grain weight per unit combined irrigation and rainwater during crop growth.

Results

Water use

Table 1 summarizes the measured and calculated values of the water balance components during the crop growth period (from sowing to harvest of the direct-seeded treatments and from transplanting to harvest for the transplanted treatment TPR). Because the direct-seeded crops were established earlier in the main plots than the TPR crop, the capture of rainfall was some 45% higher. TPR had the highest water input, followed by WSR, which had 18% less. The lower amount of percolation loss in WSR was probably due to lower depths of ponded water in the early part of the growing season, which resulted in a smaller hydraulic gradient (Wickham and Singh 1978, Bhuiyan et al 1995). Total water inputs were very low in the dry-seeded treatments, especially in the raised beds. Compared with TPR, the total water input in DSR, FB, RB_{00}, RB_{20}, and RB_{40} was 35%, 36%, 42%, 47%, and 51% less, respectively. The reduction in water input in the DSR, FB, and RB treatments was caused more by a reduction in percolation loss than by a reduction in evapotranspiration. For example, compared with TPR, the percolation loss in RB_{00}, RB_{20}, and RB_{40} was 44%, 56%, and 69% less, respectively, whereas the evapotranspiration loss was only 39%, 40%, and 42% less, respectively.

The two puddled treatments, TPR and WSR, used 360 and 265 mm of irrigation water during wet-land preparation (puddling), respectively, whereas no irrigation water was used in the dry-seeded treatments. Rainfall during the land preparation of WSR caused a lower irrigation water requirement in this treatment compared with that of TPR (land preparation for TPR was later than for WSR, hence these differences).

Yield and water productivity

Table 2 gives the yields and water productivities. The yield was highest in TPR, although, with only 5.5 t ha^{-1}, this was still quite low for an area where yields of 7 t ha^{-1} can be obtained under favorable conditions (IARI 1999). Compared with TPR, yields were 27% and 23% lower in the wet- (WSR) and dry (DSR)-seeded treatments

Table 1. Components of the water balance (mm) during the crop growth period.

Component	Treatment[a]						
	TPR	WSR	DSR	FB	RB_{00}	RB_{20}	RB_{40}
Irrigation	1,360	1,108	685	669	567	497	419
Rainfall	249	358	361	361	361	361	361
Evapotranspiration	781	710	556	494	475	466	456
Percolation	828	756	466	510	433	344	241
Change in soil storage	0[b]	0	24	26	20	48	83
Total water inflow	1,609	1,466	1,046	1,030	928	858	780
Total water outflow	1,609	1,466	1,022	1,004	908	810	697

[a]See text for explanation of treatments. [b]The soil was saturated at the start and end of the experiment.

Table 2. Rice yield (t ha^{-1}) and water productivity (WP; g grain kg^{-1} water).

Item	Treatment						
	TPR	WSR	DSR	FB	RB_{00}	RB_{20}	RB_{40}
Yield	5.5	4.0	4.2	3.2	3.2	3.1	2.5
WP_{ET}[a]	0.70	0.56	0.76	0.65	0.68	0.68	0.55
WP_{IR}[b]	0.34	0.27	0.40	0.31	0.35	0.37	0.32

[a]WP_{ET} = water productivity with respect to evapotranspiration. [b]WP_{IR} = water productivity with respect to irrigation plus rainfall.

with 20-cm row spacing. Changing the row spacing in dry-seeded rice on flat land from 20 cm (DSR) to 20-47-20 cm (FB) reduced yield by 24%. Apparently, the crop did not compensate for the reduction in planted area (having wider spacing between the rows) by producing more tillers or panicles. Rice planted on beds with 20-47-20-cm row spacing (RB_{00}) produced the same yield as rice planted on flat land with the same row spacing (FB). In the bed treatments, yield did not decline when the soil water tension increased from near-continuous saturation (RB_{00}) to 20 kPa (RB_{20}). Only when the soil was allowed to dry out to –40 kPa (RB_{40}) did the yield decrease a further 19%.

Water productivity did not vary much among treatments. Expressed per unit evapotranspiration (WP_{ET}), water productivity was highest in the TPR and DSR treatments and lowest in the WSR and RB_{40} treatments. Expressed per unit irrigation and rainwater input (WP_{IR}), the differences among treatments were very small. Any differences in water use among the treatments were offset by (opposing) differences in yield. The magnitudes of WP_{IR} are comparable with other values reported for north-central India (Bouman and Tuong 2001, Mishra et al 1990, Khepar et al 1997).

Soil nitrogen

The measured ammonium-nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N) contents in the soil are summarized in Tables 3 and 4, respectively. The NH_4^+-N content at flowering increased from the initial value (before emergence) at all depths, irrespective of the treatment. Of all the treatments, TPR had the highest contents at all depths, followed by WSR. The high NH_4^+-N content in TPR and WSR was caused by the prevailing anaerobic conditions in the soil, as these treatments were kept under continuous submergence. Also, the application of nitrogen in the form of urea, 10 days before flowering, contributed to the high NH_4^+-N content. In the dry-seeded treatments, the aerobic conditions favored the transformation of ammonium-N into nitrate-N. Our results corroborate the findings by Santra et al (1994) that the concentration of NH_4^+-N was higher under submerged paddy field conditions than under aerobic conditions. In all treatments, the NH_4^+-N contents decreased with depth.

Contrary to soil NH_4^+-N, the soil NO_3^--N content at flowering was lower than the initial value at all depths, irrespective of the treatment. In the submerged treatments TPR and WSR, the NO_3^--N content was lower in the first 15 cm than in the

Table 3. Soil ammonium-N content (kg ha^{-1}) at the start of the experiment (initial) and at flowering for the seven treatments.

Treatment[a]	Soil depth (cm)			
	0–15	15–30	30–45	45–60
Initial	29.9	20.2	21.3	13.4
TPR	135.1	102.1	74.3	29.5
WSR	89.9	58.9	54.4	23.6
DSR	78.3	46.7	39.6	26.8
FB	67.2	49.5	28.9	21.6
RB_{00}	59.4	48.2	41.6	20.9
RB_{20}	60.5	55.3	49.5	12.5
RB_{40}	51.7	34.3	29.5	17.4

[a]See text for explanation of treatments.

Table 4. Soil nitrate-N content (kg ha^{-1}) at the start of the experiment (initial) and at flowering for the seven treatments.

Treatment[a]	Soil depth (cm)			
	0–15	15–30	30–45	45–60
Initial	143.4	114.9	102.6	71.2
TPR	34.1	38.1	43.4	49.1
WSR	36.0	33.5	44.1	47.5
DSR	50.8	39.3	37.2	42.2
FB	56.2	44.5	32.4	33.1
RB_{00}	59.2	35.9	40.7	39.0
RB_{20}	58.3	30.7	51.2	32.7
RB_{40}	63.9	42.4	54.3	35.9

[a]See text for explanation of treatments.

dry-seeded aerobic treatments. At depths deeper than 30 cm, however, there were no consistent differences with the aerobic treatments anymore. In TPR and WSR, the NO_3^--N content increased with depth where conditions were aerobic and favored the transformation of ammonium-N into nitrate-N again.

Soil iron

Table 5 summarizes the measured soil iron (Fe) contents. In the dry-seeded aerobic treatments DSR, RB_{00}, and RB_{40}, the Fe content was about half of that in the submerged TPR and WSR treatments. The values of 2.1–2.6 ppm in the aerobic treatments were below the critical limit of 4.5 ppm (Lindsay and Norvell 1978).

Table 5. DTPA-extractable iron (ppm) in the soil at 0–15- and 15–30-cm depth at maximum tillering.

Treatment[a]	Depth (cm)	
	0–15	15–30
TPR	5.07	5.81
WSR	5.03	5.13
DSR	2.26	2.28
RB_{00}	2.55	2.61
RB_{40}	2.15	2.21

[a]See text for explanation of treatments.

Table 6. Nematode root-knot index during grain filling and at harvest.

Stage	TPR[a]	WSR	DSR	FB	RB_{00}	RB_{20}	RB_{40}
Grain filling	2.25	3.62	4.00	3.37	4.25	4.12	3.87
Harvest	1.67	2.87	3.50	2.62	3.25	3.88	4.75

[a]See text for explanation of treatments.

Soil nematodes

The average initial population density of the root-knot nematodes *Meloidogyne graminicola* and *M. triticoryzae* was 2 juveniles cc^{-1} soil, which was higher than the damage threshold level of 0.5 juvenile cc^{-1} soil (Gaur, personal communication, 2002). Table 6 gives the root-knot index at grain filling and harvest of the rice crop. The index is significantly lower in TPR than in the direct-seeded treatments (which have statistically the same indices).

Discussion

Dry seeding of rice and subsequent aerobic soil conditions have great potential to reduce water inputs compared with traditional flooded and transplanted rice. However, our experiment has revealed that the aerobic growing of rice faces several potential yield-reducing problems that need to be solved through the development of proper management practices. First, in our Typic Ustochrept soil, iron was deficient in all aerobic treatments. Second, an initial large nematode population in the soil led to root galling that was twice as severe under aerobic conditions as under flooded, transplanted conditions. Third, though not measured in terms of biomass or numbers, the dry-seeded aerobic treatments suffered from severe weed infestation that required a large amount of manual weeding. The data reported here are just from a single season, and more seasons of experimentation are needed to reach solid conclusions. While information on yield-reducing factors is important for the development and introduction of new systems (raised beds), such factors need to be fully controlled in future experiments to avoid confounding effects.

The aerobic cultivation of rice requires especially adapted varieties. With our cultivar Pusa-44, yields decreased rapidly with soil water tension building up in the soil. The experience in China (Yang Xiaoguang et al, this volume) shows that special aerobic rice varieties can be bred that combine a high yield potential with good drought tolerance. On raised beds, we found that Pusa-44 did not compensate for the loss in cropped area (caused by the relatively large row spacing between the beds) by producing more productive tillers.

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Physiology and breeding

Physiological characterization of rice grown under different water management systems

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In a cement-box experiment in Nanjing (China), production characteristics, water-use efficiency, nitrogen-use efficiency, and the major physiological characteristics of three alternative water management practices—the System of Rice Intensification (SRI), plastic ground-cover system (PGS), and intermittent irrigation system (IIS)—were compared with a conventional flooded rice system (CK). In addition, the effect of two nitrogen levels (150 and 300 kg ha^{-1}) was studied.

Water supply in SRI and IIS was 46% and 36% lower than in CK, respectively, whereas their yields were similar or significantly higher, 5% (SRI at 150 kg N ha^{-1}) and 8% (IIS at 300 kg N ha^{-1}), resulting in greater water-use efficiency and nitrogen-use efficiency. The higher yields of SRI and IIS compared with CK were associated with higher harvest indices but not with differences in total biomass production. Water supply and yield in PGS were 65% and 62% lower than in CK, respectively.

At jointing stage, leaf photosynthesis, transpiration rate, and stomatal conductance decreased with reduced water input. High nitrogen levels increased leaf photosynthesis and transpiration rate in IIS, SRI, and PGS more than in CK. At heading, leaf-soluble sugar, nonprotein nitrogen content, and nitrate reductase activity were higher in IIS, SRI, and PGS than in CK. Nitrogen uptake in SRI and IIS was similar to that in CK, but nitrogen redistribution from the vegetative organs to grain was larger than that in CK. High nitrogen levels increased water-use efficiency and decreased nitrogen-use efficiency in all water treatments.

Recently, various rice systems have been developed aimed at reducing the amount of water supplied in conventional lowland rice production systems: (1) controlled irrigation or wet-soil irrigation of rice, in which the soil water content is kept high without a standing water layer (Liu et al 2000); (2) thin-water-layer irrigation and draining depending on the development stage of rice, in which a thin standing-water layer exists throughout the growing season, except for transplanting, the end of effective tillering, and the heading stage (Yi 1997); (3) intermittent irrigation system, whose water management protocol is described in the section "Materials and methods" of this paper (Huang et al 1998, Zhi et al 1996); (4) plastic ground-cover system (Huang et al 1997, Wang and Liu 2001), in which the soil is covered with a plastic membrane; and (5) the System of Rice Intensification, developed in Madagascar, which shows similarities with controlled irrigation (Razakamiaramanana et al 1997, Laulanie 1993).

These rice systems decrease water losses by reducing seepage, percolation, and evaporation, thus increasing overall water-use efficiency (WUE) of rice systems (Yang et al 2000, Liang et al 2000). In addition, such systems may reduce nitrogen losses because water flows with dissolved nitrogen are reduced, thus resulting in higher nitrogen-use efficiency (NUE). Until now, the WUE and NUE of different water management systems in rice have not been systemically evaluated. In addition, reports on the physiological characteristics of rice plants under different water management are scarce.

Objectives of experiment

The aim of this study is to characterize the yield, WUE, and NUE of different water management practices in rice systems, and to explain the physiological basis for differences in yield, WUE, and NUE of these systems. In this study, WUE is defined as the grain yield divided by the amount of irrigation water supplied and NUE is defined as the N uptake of grains divided by the amount of fertilizer supplied. On the basis of well-founded information, high-yielding rice systems with a high WUE and NUE can be designed.

Materials and methods

In 2001, japonica rice cultivar Wuxiangjing 9 (9325) was transplanted in cement boxes at Nanjing Agricultural University (32°04′N, 118°48′E). The size of the boxes was 1 × 1 × 0.8 m (length × width × height) each, and they were filled with clay soil, mixed with PK fertilizer at 135 kg P_2O_5 ha^{-1} and 210 kg K_2O ha^{-1}. Total soil nitrogen content was 0.09%, available phosphorus content was 55 mg kg^{-1}, and saturated moisture content was 26%. The cement boxes were sealed at the bottom to prevent percolation and were covered with a transparent roof to avoid interference from rainfall.

Four water management systems were applied: conventional submerged (CK), intermittent irrigation (IIS), the System of Rice Intensification (SRI), and plastic ground cover (PGS). Table 1 shows the water management protocol of each system. Under nonflooded conditions, the soil surface layer (upper 10 cm) was sampled daily with a core sampler and the soil water content was determined. When the soil water content reached a well-defined threshold value, irrigation water was supplied till soil saturation or flooding conditions, depending on the treatment (Table 1). For each water management system, two nitrogen treatments were applied: 150 and 300 kg ha^{-1}, of which 50% was applied at transplanting, 10% at tillering, and 40% at heading. In

Table 1. Number of emerged leaves of rice seedlings at transplanting (ELN) and threshold values for water control at different development stages for different water management treatments: (1) transplanting to regreening stage (7 d), (2) regreening to effective tillering termination stage, (3) effective tillering termination to jointing stage, (4) jointing to penultimate leaf emergence stage, (5) penultimate leaf emergence to 10 days after heading, (6) 10 d after heading to maturity.

Treatments	ELN	Water layer (cm) or percentage soil moisture saturation (%)					
		1	2	3	4	5	6
CK	6	3–5 cm	1–5 cm	1–5 cm	1–5 cm	1–5 cm	1–5 cm
IIS	6	3–5 cm	3 cm–85%	3 cm–70%	3 cm–70%	3 cm–85%	3 cm–75%
SRI	3	1–3 cm	100–85%	100–70%	100–70%	100–85%	100–75%
PGS	6	100–90%	100–75%	100–75%	100–75%	100–75%	100–75%

SRI, seedlings with three emerged leaves were used at transplanting instead of six leaves in the other systems (Uphoff 2001).

Two seedlings per hill were transplanted with 25-cm row spacing and 15-cm within-row spacing. The experiment was a random block design with three replications per treatment.

Plant sampling was at transplanting, effective tillering stage, jointing, heading, and maturity. One hundred seedlings were sampled at transplanting and two to five hills of representative plants were sampled at other stages. Half of the samples were oven-dried (80 °C) to determine dry weight and nitrogen content, and the other half were used as fresh material for measuring physiological characteristics.

Total nitrogen and nonprotein nitrogen content of rice plants were determined by the Kjeldahl method. The content of soluble sugar was determined according to the anthracenone method (Zhang 1985).

Leaf photosynthesis rate, transpiration, and stomatal conductance were measured at the jointing stage with a CI-310 portable photosynthesis device (CID Incorporation, USA). Leaf water potential was measured at the jointing and heading stage with a HR33TR Dew Point Microvoltmeter (WESCOR Corporation, USA).

Results

Irrigation water, yield, WUE, and NUE

All three alternative water management systems were supplied with less irrigation water than CK (Table 2). Irrigation water supplied to IIS and SRI was about half of that supplied to CK. PGS received one-third of the water applied to CK, while nonsaturated soil conditions lasted 109 days, much longer than in SRI and IIS.

At 150 kg N ha^{-1}, the yield of SRI was significantly (5% level) higher than that of the other water treatments, whereas, at 300 kg N ha^{-1}, the yield of IIS was significantly (1% level) higher than that of the other treatments (Table 2). Yield, biomass, and harvest index of PGS were significantly lower than those of the other water treatments at both nitrogen levels. The higher yields of SRI and IIS compared with CK

Table 2. Amount of water supplied, yield, water-use efficiency (WUE), and nitrogen-use efficiency (NUE) of different water management treatments (RWM) with two nitrogen rates. Small letters refer to significant difference at 5% probability level; capital letters refer to significant differences at 1% probability level.

Nitrogen rate (kg ha^{-1})	RWM	Supplied irrigation water (t ha^{-1})	A[a] (d)	Production component			WUE (kg t^{-1})	NUE (kg kg^{-1})
				Yield (kg ha^{-1})	Biomass (kg ha^{-1})	Harvest index		
150	CK	10,130	0	6,330 bB	12,562 bB	0.410 abAB	0.51 dE	39.9 aABC
	IIS	6,500	59	6,354 bB	13,103 bB	0.423 aA	0.83 cCD	42.4 aAB
	SRI	5,470	96	6,651 bAB	13,209 bB	0.434 aA	1.00 bBC	44.3 aA
	PGS	3,610	109	2,349 cC	8,782 dD	0.239 dC	0.55 dE	31.3 bcBCD
300	CK	10,220	0	7,936 aAB	18,910 aA	0.369 cB	0.71 cDE	25.1 cdD
	IIS	6,520	59	8,630 aA	20,103 aA	0.392 bcAB	1.13 abAB	28.8 cdBCD
	SRI	5,500	96	7,965 aAB	19,139 aA	0.383 bcAB	1.24 aA	27.5 cdCD
	PGS	3,560	109	3,128 cC	11,862 cC	0.216 dC	0.72 cDE	20.9 dD

[a]A = number of days under nonsaturated soil conditions.

were associated with higher harvest indices but not with differences in total biomass production. WUEs of IIS and SRI were significantly higher than that of CK. At both nitrogen rates, NUEs of SRI and IIS were significantly higher than that of CK. The NUE of PGS was lower than that of CK, but WUE did not differ much.

The high nitrogen rate increased yield, biomass, and WUE and decreased harvest indices and NUEs of IIS, SRI, and CK. The yield and harvest index of PGS were not affected by nitrogen levels.

Physiological characteristics

Leaf water potential. Leaf water potential decreased with reduced water supply at both the jointing and heading stage (Fig. 1). However, the leaf water potentials of CK and IIS did not show significant differences, whereas the leaf water potentials of SRI and PGS were much lower than those of CK and IIS. Therefore, SRI and PGS plants suffered more from drought stress than IIS plants, while the latter treatments suffered little drought stress compared with CK. At jointing, the leaf water potential of CK at 150 kg N ha^{-1} was slightly lower than that at 300 kg N ha^{-1}. The leaf water potentials of IIS, SRI, and PGS at 150 kg N ha^{-1} were higher than those at 300 kg N ha^{-1}. At heading, little difference existed in leaf water potentials from 150 to 300 kg N ha^{-1}.

Photosynthesis rate, transpiration, and stomatal conductance. At 150 kg N ha^{-1}, the rate of leaf photosynthesis of SRI and PGS decreased by 29% and 42%, respectively, compared with CK. The leaf photosynthesis rate of IIS was similar to that of CK for both nitrogen levels. At 300 kg N ha^{-1}, photosynthesis of SRI and PGS decreased by 10% and 36%, respectively, compared with CK. At 300 kg N ha^{-1}, the photosynthesis rates of the reduced water input systems (IIS, SRI, PGS) increased more than the photosynthesis rate of CK. This indicates that nitrogen improved assimilation, especially under reduced water supply.

Leaf transpiration rate also decreased with reduced water supply, especially for SRI and PGS, because of the sharp decrease in leaf stomatal conductance (Table 3).

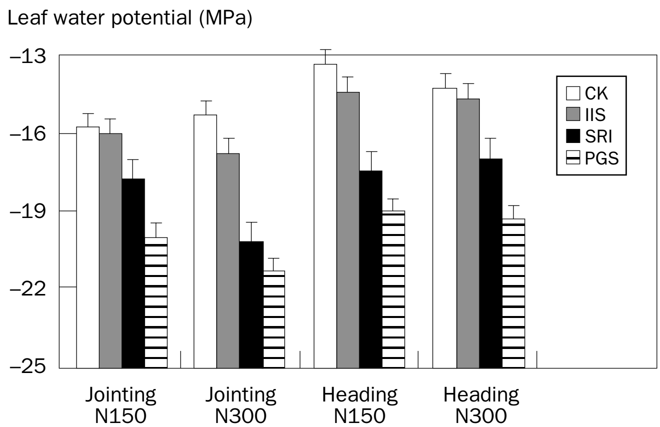

Fig. 1. Leaf water potential of different water management treatments with two nitrogen rates (150 and 300 kg ha^{-1}).

Sugar and nonprotein nitrogen content and nitrogen reductase (NR) activity. In the three alternative water management systems, soluble sugar and nonprotein nitrogen content and NR activity in rice leaves at the heading stage increase compared with CK (Table 4), indicating that carbon and nitrogen assimilation are enhanced in the alternative water management systems. At a high nitrogen rate, soluble sugar content and nonprotein nitrogen content decreased, whereas NR activity increased in all treatments.

Redistribution of dry matter and accumulation and redistribution of nitrogen

Dry matter redistribution. Dry matter redistribution from vegetative organs (leaves, stems, and sheathes) to grain between heading and maturity improves with decreasing water supply (Table 5). The redistributed fractions, that is, the difference in dry matter of vegetative organs between heading and maturity divided by dry matter of vegetative organs at heading, were also higher in the alternative water management treatments. Redistributed fractions decrease at high nitrogen rate.

Tabel 3. Photosynthesis rate, transpiration, and stomatal conductance of different water management treatments (RWM) at jointing with two nitrogen rates. Standard deviation in parentheses.

Nitrogen rate (kg ha^{-1})	RWM	Photosynthesis rate (µmol CO_2 m^{-2} s^{-1})	Transpiration rate (mmol m^{-2} s^{-1})	Stomatal conductance (mmol m^{-2} s^{-1})
150	CK	16.7 (0.67)	3.83 (0.12)	71.1 (2.40)
	IIS	15.9 (0.26)	3.27 (0.06)	52.2 (1.66)
	SRI	11.9 (0.35)	2.10 (0.10)	29.1 (1.03)
	PGS	9.7 (0.12)	1.50 (0.01)	25.5 (0.90)
300	CK	18.9 (0.85)	3.97 (0.06)	63.4 (0.95)
	IIS	18.8 (0.58)	3.57 (0.03)	67.3 (1.97)
	SRI	17.0 (0.82)	2.97 (0.06)	21.3 (0.40)
	PGS	12.1 (0.35)	2.47 (0.02)	22.0 (0.71)

Table 4. Content of soluble sugar and nonprotein nitrogen and nitrate reductase (NR) activity in the top four leaves of rice at the heading stage under different water management treatments (RWM) and two nitrogen levels. Standard deviation in parentheses.

Nitrogen rate (kg ha^{-1})	RWM	Soluble sugar content (µmol g^{-1} fresh weight)	Nonprotein nitrogen content (%)	NR activity (µg NO_2 h^{-1} g^{-1} fresh weight)
150	CK	282.38 (16.15)	0.84 (0.02)	22.13 (1.26)
	IIS	359.14 (20.98)	0.91 (0.05)	25.05 (1.81)
	SRI	438.77 (37.80)	1.08 (0.11)	39.28 (4.72)
	PGS	469.24 (45.05)	1.10 (0.08)	51.51 (2.97)
300	CK	198.51 (17.81)	0.77 (0.07)	38.27 (5.38)
	IIS	206.22 (8.11)	0.79 (0.05)	55.89 (2.74)
	SRI	320.63 (20.38)	0.95 (0.01)	63.93 (6.43)
	PGS	378.64 (27.08)	1.04 (0.05)	76.84 (1.81)

Nitrogen uptake and redistribution. Total nitrogen uptake at maturity was significantly higher at 300 kg N ha^{-1} but did not differ much among CK, IIS, and SRI at both nitrogen levels. Nitrogen uptake in PGS was significantly reduced compared with that of the other systems (Table 6). Nitrogen redistribution from vegetative organs to grain between heading and maturity was significantly higher in IIS and SRI than in CK and PGS. The nitrogen redistribution fractions, that is, the difference in nitrogen of vegetative organs between heading and maturity divided by nitrogen in vegetative organs at heading in all alternative water management treatments, were higher than in CK.

Table 5. Dry matter redistribution from vegetative organs to grain between heading and maturity under different water management treatments (RWM) and two nitrogen levels. See Table 2 for explanation of the letters indicating different significance levels.

Nitrogen rate (kg ha^{-1})	RWM	Redistributed dry matter (kg ha^{-1})	Redistributed fraction
150	CK	773 dCD	0.131
	IIS	884 cdBC	0.140
	SRI	1,056 bB	0.186
	PGS	951 bcBC	0.214
300	CK	629 ed	0.078
	IIS	833 cdC	0.096
	SRI	1,229 aA	0.148
	PGS	1,038 bB	0.177

Table 6. Total nitrogen uptake at maturity and redistributed nitrogen from vegetative organs to grain between heading and maturity under different water management treatments (RWM) and two nitrogen levels. See Table 2 for explanation of the letters indicating different significance levels.

Nitrogen rate (kg ha^{-1})	RWM	Total uptake (kg ha^{-1})	Redistributed nitrogen (kg ha^{-1})	Redistributed fraction
150	CK	121.71 cB	23.60 eD	0.290
	IIS	122.99 cB	31.43 cdC	0.374
	SRI	109.57 cB	31.77 cC	0.417
	PGS	61.14 dC	19.91 fE	0.426
300	CK	203.67 abA	30.45 dC	0.241
	IIS	216.74 aA	45.91 bB	0.331
	SRI	196.79 bA	50.93 aA	0.383
	PGS	109.94 cB	32.16 cC	0.405

Conclusions

The water supply in SRI and IIS was 46% and 36% less than in CK, respectively, whereas yields were similar or higher, resulting in a higher WUE in SRI and IIS. Higher yields in SRI and IIS were associated with higher harvest indices, but biomass production and nitrogen uptake were similar in CK, SRI, and IIS. The redistribution fractions of both dry matter and nitrogen were higher in IIS and SRI than in CK and PGS. The water supply in PGS was so low that yields and other characteristics are clearly different from those of other treatments.

This study showed that we can reduce the amount of water in conventional irrigated rice systems without reducing yield. In addition, two alternative water management systems performed better than the conventional flooded system, that is, SRI at 150 kg N ha^{-1} and IIS at 300 kg N ha^{-1}.

In this study, we used soil water content in the water management protocol as an indicator for the supply of irrigation water. Measurement of soil water content was slow and problematic since it is easily prone to error and therefore seems not to be the most appropriate tool to support irrigation decisions. Rapid, accurate, and easy-to-use monitoring and diagnosis tools are urgently needed to assess the water status of rice systems and to support irrigation decisions. Such tools facilitate informed decision making for water management and are crucial to developing high-yielding rice systems with high WUE and NUE.

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Notes

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Requirements for aerobic rice: physiological and molecular considerations

H.R. Lafitte and J. Bennett

Rice evolved from a semiaquatic ancestor, which was then domesticated into lowland or aerobic cultivars. Aerobic cultivars maintain many obvious semiaquatic adaptations, such as the development of aerenchyma in roots, a superficial root system, and high levels of nonstomatal water loss from leaves. There is a similar tendency to conserve adaptations to excess water at the cellular and molecular levels. For rice to succeed as an aerobic crop, breeders must overcome the legacy of anaerobic adaptation, enabling the crop to tolerate intermittent water deficits, high soil impedance, and low relative humidity. Extensive genetic variation exists within cultivated *Oryza sativa* and additional variation is present in wild rice relatives. Dramatic contrasts are observed among rice cultivars in the response of root growth to soil drying; some cultivars cease root development, some increase root mass in superficial layers, and others show increased root growth at depth. Genetic variation is also observed in the sensitivity of rice leaf area expansion to both soil and atmospheric water deficit, and in the relative reduction in spikelet number and fertility that occurs in aerobic conditions. All three of these processes, drought rhizogenesis, leaf expansion, and sink pruning, are expected to reflect differences in signal reception and transduction in rice compared with other crops. Improved understanding of the molecular basis and genetic control of these signaling processes will facilitate the development of successful aerobic cultivars that respond to the environment more like other upland crop species.

Aerobic cultivation of rice is a technology that can allow for substantial water savings, as documented by other authors in this volume. In this system, the soil is not saturated for most of the season and roots grow in an aerobic environment, similar to other crops such as maize or wheat. A key component of success in aerobic systems is appropriate cultivars, as described by Wang Huaqi et al (this volume). In developing these cultivars, breeders may need to reverse some of the evolutionary pressures that have allowed rice to become a highly productive crop in flooded soils. The goal of this paper is to review some of the morphological and physiological adaptations to saturated soil conditions that are found in rice, and to contrast these with the characteristics of other species that are adapted to aerobic soils. This comparison may provide a better understanding of the traits that should be modified in rice to allow it to succeed as a component of aerobic water-saving systems.

Cultivated rice apparently evolved from a semiaquatic, perennial ancestor (Chang 1976, Kellogg 2001). Farmer selection has resulted in the differentiation of upland and lowland cultivars. The distinction between upland and lowland cultivars is qualitative, and there is a gradation between the two ecotypes for most characteristics. Most upland cultivars grow successfully in flooded conditions and most lowland cultivars can survive in well-watered aerobic soils.

The wetland ancestry of rice is reflected in several morphological and physiological characteristics that are unique among crop species. To design rice varieties that are better adapted to aerobic cultivation systems, we need to consider the semiaquatic traits that may stand between rice and high, stable yields in unflooded soils. In many cases, examples of superior alleles for these traits will be found in upland rice varieties, which have been selected by generations of rice farmers for performance in aerobic environments. Other traits are mediated by genes that may have become fixed in cultivated rice; for such traits, it may be necessary to seek superior alleles in wild *Oryza* species or even in other crops.

Key differences between rice and other cereals include shoot and root anatomy and water loss patterns, growth responses to soil water status in the range from saturation to the point of reirrigation, and the response of reproductive structures to water deficit. The range of genetic variation within *Oryza sativa* is reported where available and compared with that of other crop species.

Morphology

Shoots

Rice leaves are generally thin, with no differentiation of mesophyll cells into palisade and spongy parenchyma. These characteristics are common in plants from shady habitats (Givnish 1988). Rice apparently separated evolutionarily from other Gramineae before grasses moved from the forest floor to more open, high-radiation habitats (Kellogg 2001). Leaves are particularly thin in the indica subspecies. The japonica subspecies generally has thicker leaves, but the underlying leaf anatomy is similar to that of indica types. The number of stomata is tenfold greater than in the leaves of dryland species, stomata are small in size, and cultivars differ in the effect of environment on stomatal frequency (Yoshida and Ono 1978). This is in contrast to the traits normally observed in shade plants. The vascular system in rice is characterized by xylem vessels of small diameter (Lafitte et al 2001).

Rice cuticles are thin, with less than 5% of the wax load of other crops. Although the wax load per se is not directly related to cuticular water loss (Kerstiens 1996), cuticular resistance is comparatively low in rice (Table 1). Cultivar differences are known, with upland cultivars having more wax (O'Toole et al 1979). There is a

Table 1. Morphological traits of upland and lowland rice and other upland crop species.

Trait	Value	Reference and notes
Stomatal frequency (per mm²)		
Rice (av both sides)	300–400 (range 150–650)	Varies with cultivar and environment; Matsuo et al (1995)
Oat	50	Kramer and Boyer (1995)
Maize	100	Kramer and Boyer (1995)
Cuticular resistance (s cm⁻¹)		
Flooded rice	50 (IR20), 68 (upland)	O'Toole et al (1979)
Water-stressed rice	80 (IR20), 100 (upland)	O'Toole et al (1979)
Maize	112	O'Toole et al (1979)
Sorghum	116	O'Toole et al (1979)
Rice, upland conditions	10–30	Epidermal resistance based on water loss from excised leaves; Mitchell et al (1998)
Root metaxylem diameter (µm)		
Lowland rice, unflooded	40	Yambao et al (1992)
Upland rice, unflooded	60	Yambao et al (1992)
Wheat	60–65	Richards and Passioura (1989)
Root length density, 0–20 cm		
Lowland rice, unflooded	8–14	Fukai and Inthapan (1988)
Sorghum	10	Fukai and Inthapan (1988)
Maize	7	Fukai and Inthapan (1988)
Sorghum	0.3	Robertson et al (1993)
Lowland rice, unflooded	8–9	Chang et al (1982)
Upland rice, unflooded	3–4	Chang et al (1982)
Water uptake per unit root length (aerobic) ($cm^3\ cm^{-1}\ d^{-1}$)		
Upland rice (C-171-136)	0.001	Soil water content >50%, 60–80 cm depth, Angus et al (1983)
Cowpea	0.012	Soil water content >50%, 60–80 cm depth, Angus et al (1983)
Upland rice	0.005 at –0.1 MPa soil	10–15 cm depth; Angus et al (1983)
Lowland rice (CPIC8)	0.002; root length density = 5	With water deficit; Lilley and Fukai (1994a)
Upland rice (Rikuto-Norin 12)	0.004; root length density = 2	With water deficit; Lilley and Fukai (1994a)
Sorghum	0.01–0.03	65–165 cm depth, soil fraction of extractable water 0.8 to 0.5; Robertson et al (1993)
Maximum root depth (cm)		
Lowland rice (IR36)	40	With significant water stress; Angus et al (1983)
Upland rice (C-171-136)	60	With significant water stress; Angus et al (1983)
Maize	90	With significant water stress; Angus et al (1983)

strong correlation between epicuticular wax content and root xylem vessel diameter (Lafitte et al 2001). Rice panicles are also characterized by thin cuticles. Silica is gradually deposited on the glumes after flowering and transpiration declines (Garrity et al 1984). About 30% of the water transpired by lowland rice after flowering is lost through panicles and this reflects a maximum resistance of about 3 s cm^{-1} in panicles compared with leaf diffusive resistance up to 5 s cm^{-1} in the same plants (Ekanayake et al 1993).

- *Implications for aerobic rice*

The absence of a palisade layer, many small stomata, and high cuticular water loss are not incompatible with productivity in humid, cloudy monsoonal regions in the wet season, or with high radiation as long as fields are flooded. Substantial unproductive water loss through cuticles does become a problem when water availability is limited, as in aerobic systems. Silica availability in aerobic systems is also lower, and this can slow the process of exodermal silicification of panicles, leaving them subject to desiccation. There is substantial genetic variation in rice for epicuticular wax deposition, though levels are much lower than in dryland species. Ongoing efforts to transform rice for greater cuticular wax deposition will, if successful, allow a test of the value of increasing cuticular resistance to the levels of other crops.

Roots

In comparison with other crops, the rice root system is very compact. The number of lateral roots in upland rice is about 24 per cm of nodal root, while it is 7 per cm in maize (Yamauchi et al 1987). Maize roots are longer and developed at a more oblique angle, so maize explores a larger soil volume. As a result of dense branching and limited root length, rice root length density in the surface soil (0–20 cm) is usually several times greater than in other crops (though some reports are contradictory; see Table 1). This pattern is observed in both upland and lowland conditions, with root growth below 20 cm being less than 15% of the total root mass (Iwama and Yamaguchi 1996). Cultivar differences exist: in a dryland field, upland cultivars had less root length above 20 cm and more root length below 30 cm than lowland cultivars (O'Toole and Bland 1987). Differences in the patterns of root distribution have been documented both among and within rice ecotypes (Lafitte et al 2001). The root system extension in depth is slower for rice than for other crops, and the maximum rooting depth is generally less. Cultivar differences have been found in whether root mass depth increases (drought rhizogenesis), remains unchanged, or decreases as the surface soil dries (Morita and Abe 1996). Reports on the sensitivity of root growth to soil strength are contradictory, but it appears that rice is significantly less capable of penetrating compacted soils than are other crops, with a critical mechanical impedance of about 0.5 to 1.0 MPa (Table 1). This level is exceeded in most unflooded soils.

Rice roots constitutively form lysigenous aerenchyma under both aerobic and anaerobic conditions, though the size of the air spaces is smaller in aerobic soils (Drew et al 2000). They also constitutively form an exodermis (or hypodermis), a layer of cortical cells just inside the epidermis that is characterized by having a suberized band in the cell walls similar to the Casparian strip of the endodermis. In flooded conditions, the suberized layer apparently does not represent a significant barrier to water absorption. Upon exposure to air, the permeability of the exodermis drops drastically (Clarkson et al 1987). Water absorption may be limited to the unsuberized apical zone and regions where lateral roots penetrate the exodermis. Uptake can also occur via unsuberized passage cells in the exodermis (Peterson and Enstone 1996). In addition to limiting the physical capacity for uptake, restriction of uptake to a small area can result in the development of an apparent interfacial resistance to water absorption because of the accumulation of solutes in that soil region (Stirzaker and Passioura 1996). Existing studies indicate that the hydraulic conductance of rice roots is comparatively low, but the relative roles of the exodermis, aerenchyma, and endodermis require further clarification (Miyamoto et al 2001).

While rice roots appear to dry the surface soil to at least the same levels as other crops, it appears that rice under stress extracts less water per unit length from depth than other crops. In a comparison among rice, maize, and sorghum, rice extracted significantly less water per cm of root from below the 60-cm layer than did the other crops (Fukai and Inthapan 1988). Under less severe stress, however, rice extracted more water per unit root length than maize at depths of 20 to 40 cm, and had similar water extraction rates as maize in the 40- to 60-cm soil layer (Kondo et al 1999). The incomplete extraction of water by rice from depth in drying soil suggests that there may be some significant resistance to water flow within rice roots. Although whole-plant resistance to water transport is similar in flooded rice and other crops, resistance is greater in unflooded plants, and all of the difference has been related to greater root resistance in unflooded plants (Tomar and Ghildyal 1973).

- *Implications for aerobic rice*

In aerobic systems, rice roots must fully explore the soil profile and effectively absorb water at deeper layers. This will require deeper rooting than is observed in most high-yielding tropical cultivars. At the same time, the ability to form aerenchyma and survive flooding must be maintained for those target environments where intermittent waterlogging can occur. To date, no data have been found that associate the formation of constitutive aerenchyma with poor growth in aerobic soils.

Crop response to water deficit

Rice water relations appear to differ from those of dryland crops in certain aspects. Leaf water potential in flooded rice is generally similar to that in well-watered dryland crops. Afternoon leaf water potentials are low in environments with high vapor pressure deficits, and the afternoon decline in photosynthesis is pronounced in rice, even under well-watered conditions (Turner et al 1986). In dryland conditions, rice tended to have lower midday water potential than maize or sorghum even when the soil was well watered (–2 to –3 MPa, compared with –1 MPa for maize and sorghum, Table 2; Inthapan and Fukai 1988). In a study where water was applied to equal 100% pan evaporation 2 to 3 times each week, midday leaf water potential varied from –0.8

Table 2. Physiological traits and agronomic performance of upland and lowland rice and other upland crop species.

Trait	Value	Reference and notes
Soil water status where leaf area affected		
Lowland rice	Soil water potential (MPa) = –0.05 to –0.16 (dry season); –0.05 to –0.26 (wet season)	Wopereis et al (1996)
Upland rice	Remaining fraction of extractable water = 0.8	Lilley and Fukai (1994b)
Sorghum	Remaining fraction of extractable water = 0.25	Sadras and Milroy (1996)
Midday leaf water potential (MPa)		
Rice, aerobic	–2.0 to –2.8 irrigated, –2.8 to –3.3 rainfed	Fukai and Inthapan (1988)
Maize	–1.0 irrigated, –1.8 rainfed	Fukai and Inthapan (1988)
Sorghum	–1.2 irrigated, –1.8 rainfed	Fukai and Inthapan (1988)
Grain yield (Mg ha^{-1})		
Lowland rice	3.6 irrigated, 0 rainfed	Irrigated weekly; Inthapan and Fukai (1988)
Upland rice	6.8 irrigated, 0.6 rainfed	Irrigated weekly; Inthapan and Fukai (1988)
Maize	10.6 irrigated, 5.5 rainfed	Irrigated weekly; Inthapan and Fukai (1988)
Sorghum	12.4 irrigated, 7.2 rainfed	Irrigated weekly; Inthapan and Fukai (1988)
Lowland rice (IR36)	2.6 irrigated, 0 rainfed	Irrigated every 7–14 d; Angus et al (1983)
Upland rice (CT1171-136)	3.6 irrigated, 0 rainfed	Irrigated every 7–14 d; Angus et al (1983)
Maize	6.8 irrigated, 4.1 rainfed	Irrigated every 7–14 d; Angus et al (1983)
Sorghum	7.6 irrigated, 4.8 rainfed	Irrigated every 7–14 d; Angus et al (1983)
Floret sterility (%)		
Lowland rice (IR36)	20 at ψ_{leaf} = –0.9 MPa; 73 at ψ_{leaf} = –2.5 MPa	Cruz and O'Toole (1984)
Upland rice (IRAT 13)	10 at ψ_{leaf} = –0.9 MPa; 75 at ψ_{leaf} = –2.5 MPa	Ekanayake et al (1989)
Wheat	50 at ψ_{leaf} = –5.0 Mpa; 25 at ψ_{leaf} = –3.0 MPa	Westgate et al (1996)

to –1.3 MPa, and the trial was considered to experience permanent mild water stress (Dingkuhn et al 1989). Dryland crops such as maize or wheat have no need for such a high irrigation frequency. These crops do not generally experience water stress until more than 50% of the available soil moisture has been lost, but processes of leaf expansion (Table 2) and transpiration in rice are affected as soon as the soil drops below saturation in some cultivars, and when only about 30% of the available soil water has been extracted in cultivars with aerobic adaptation (Lilley and Fukai 1994b). This is not a severe level of drought—it is a normal condition that is expected between irrigation events in dryland crops.

In rice, stomatal closure begins at higher leaf water potential than in other crops and transpiration declines gradually, starting at about –0.75 MPa (Dingkuhn et al 1989). These values vary with preconditioning, and in lowland rice stomatal conductance begins to decline at –0.2 MPa (Hirasawa et al 1987). Models indicated that, in lowland rice, transpiration declined as soon as soil moisture declined below saturation, as opposed to field capacity in dryland crops (Wopereis et al 1996). Leaf area expansion in rice is also extremely sensitive to soil water status, with an apparent response between saturation and field capacity. The leaf area index of IR54 decreased relative to a flooded control when soil water content dropped from 75% (flooded) to 70%, corresponding to a change in midday water potential from about –0.8 to –0.9 MPa (Cruz et al 1986). Mild temporary water stress resulted in a 27% reduction in grain yield in IR54, and similar reductions are reported when rice is grown in well-watered conditions (soil water potential of –0.05 MPa) relative to flooded conditions (Table 2). A major effect was on tiller number, but it has also been found that crop growth rate around anthesis is closely related to the number of spikelets per panicle and the unfilled grain percentage in water-limited rice (Boonjung and Fukai 1996).

- *Implications for aerobic rice*

If upland rice cultivars are to yield well in environments where soil water potentials frequently drop below field capacity, the crop response to soil moisture supply must be shifted toward the pattern found in other upland crops. Leaf area expansion and tillering habits should remain unaffected across the range of soil conditions from fully saturated to below field capacity. It is not sufficient to select for the desired plant type in aerobic soils because intermittent flooding in some seasons may then produce a tall, leafy, and possibly early plant that will not match the cultural conditions used by the farmer. In addition to stability of plant type across water environments, aerobic rice requires decreased sensitivity to mild water deficit (7 to 10 days without rainfall) at flowering.

Signaling patterns in rice

Roots of flooded plants generally experience high concentrations of ethylene because ethylene is unable to diffuse out of the root (Drew et al 2000). In the aerobic situation, root ethylene concentrations will be lower. The response of root elongation to ethylene appears to be positive up to a threshold level and then growth declines with increasing ethylene. Growth of rice roots is less sensitive than other crops to endogenous levels of ethylene (Table 3). Root extension in mustard declines at ethylene levels of 0.1 μL L^{-1}, but rice root growth does not decline until levels reach 0.8 μL L^{-1} (Reid 1995). Rice also produces less ethylene than other crops, though considerable variation occurs among cultivars (Jackson 1985). In general, it appears that crops producing less ethylene grow more slowly and they are also less sensitive to additional ethylene. Thin roots accumulate less ethylene under flooding than thick ones and are less likely to experience large reductions in root growth. The adaptations of lowland rice cultivars are consistent with success in flooded habitats: low ethylene production and sensitivity plus thin roots mean that root ethylene levels are generally in the growth-promoting range. If rice roots are less sensitive to ethylene, however, their ability to penetrate compacted soils might be impaired, especially in aerobic conditions where ethylene can diffuse out of the tissue easily and thus will not reach growth-promoting levels.

Growth of certain aerial parts is generally enhanced by ethylene in aquatic plants but is reduced by ethylene in dryland plants. In rice, the sensitive zones are the coleoptile and mesocotyl. Ethylene increases the sensitivity of rice coleoptiles to auxin and the sensitivity of internodes to gibberellic acid (GA) in deepwater rice (Hoffman-Benning and Kende 1992). These responses contrast with those of most cultivated plants, where auxin or GA and ethylene have opposite effects. Cultivars differ in the response of coleoptile elongation to ethylene. In aerobic soils, the key factors for rapid elongation of the coleoptile (low O_2, high CO_2, and high ethylene) are absent, and this can affect crop emergence.

Table 3. Concentrations and activities of some growth regulators in rice and other crops.

Trait	Value	Reference and notes
Minimum ethylene concentration to reduce root extension (μL L^{-1})		
Rice	0.8–1.0	Jackson (1985)
Maize	0.1	Jackson (1985)
Rye	0.001	Jackson (1985)
ABA accumulation in detached leaves (ng g^{-1} fresh weight)		
Lowland rice	825	Austin et al (1982)
Upland rice	365	Austin et al (1982)
Wheat	280	Austin et al (1982)
Millet	210	Austin et al (1982)
ABA concentration in xylem sap (nM)		
Lowland rice, flooded	5–15	Asch et al (1995)
Lowland rice, unflooded (IR36)	7 control; 20 with some roots dry; 92 with drought	Bano et al (1993)
Maize and sunflower	10 control; 100 or more with drought	Tardieu et al (1992)

Another key signaling molecule in plants is abscisic acid (ABA), a growth substance involved in many of the responses to plant and soil water status. Leaf conductance and leaf area expansion respond to soil water deficit well before there is any change in leaf water potential (Tardieu and Davies 1993), and root-sourced ABA has been implicated as an important signal. In rice, exposure of part of the root system to air led to stomatal closure and a 56% increase in xylem ABA content after 2 hours (Bano et al 1993). When part of the soil volume was allowed to dry, stomatal conductance declined and xylem ABA increased, even though there was no change in shoot water status. There was also a decrease in cytokinins in xylem sap. In another study, rice cultivars were found to differ in the sensitivity of stomata to xylem ABA (Asch et al 1995). The relationship between xylem ABA and stomatal conductance was found to depend on relative humidity, which might sensitize the stomata to the root-sourced signal. Insufficient data are available to fully characterize rice response to ABA, but it appears that the pattern of response is generally similar to that of other cultivated plants. An upland rice cultivar was found to be less sensitive to exogenous ABA than a lowland cultivar (Bois et al 1993).

The ABA response of coleoptile elongation in rice was found to differ from that of other crops such as wheat, oats, and barley (Hoffman-Benning and Kende 1992). An inhibitor of ABA synthesis reduced coleoptile elongation in rice, but not in other species. The response of rice root elongation to ABA appears to differ among cultivars (R. Lafitte, unpublished data). Extensive and complex patterns of interaction have been documented between ABA and ethylene, and with other growth substances as well (Gazzarrini and McCourt 2001). Ethylene appears to generally interfere with ABA signaling (Ross and O'Neill 2001). Lower tissue ethylene concentrations in aerobic systems may lead to greater sensitivity of aerobic rice to mild water stress or high evaporative demand.

ABA accumulation in grains has also been associated with spikelet fertility, but it did not seem that root-sourced ABA was the major factor in wheat (Westgate et al 1996). In contrast, drying of part of the root system affected seed set in rice, independent of changes in shoot water status (Kobata et al 1994). The two crops may differ in the production of a signal by the root or in the sensitivity of grain set to the signal.

- *Implications for aerobic rice*

Our understanding of the interactions between growth substances and performance of rice is not yet sufficient to allow a recommendation on the type of ethylene and ABA responses needed in aerobic rice cultivars. Therefore, selection for these responses cannot be recommended. It will be more helpful to select for stability of plant type and yield across the potential range of target environments, and define subenvironments when stability cannot be achieved.

Plant type

Modern, highly productive lowland rice cultivars are semidwarf types and most incorporate the *sd1* gene as the source of reduced plant height. This gene results in reduced GA concentration in the plant (Ashikari et al 2002) and reduced height. Quantitative trait loci (QTL) analyses indicate that genetic regions near *sd1* are also associated with tiller number and panicle length, and individuals with dwarf height have more tillers and shorter panicles (Huang et al 1996). Drawbacks to this plant type for aerobic conditions are fairly poor weed competitiveness and a pronounced reduction in plant height in dry soils. In addition, many semidwarf types tend to have large reductions in harvest index in mildly stressful aerobic conditions (Lafitte et al 2002). This may reflect unfavorable interactions between GA and ABA levels. The tall, low-tillering plant type, found in many traditional upland cultivars, is also not suitable for intensive aerobic rice systems because these plants lodge with high inputs and do not have the necessary yield potential. This is an example of where traits that confer an advantage in one environment represent a liability in another (see Table 4 for plant characteristics that favor success in the wild but are disadvantageous in cultivated systems). Alternate sources of height reduction may be needed to produce a suitable plant type for intensive aerobic rice systems. Successful aerobic breeding programs in China and Brazil have achieved an intermediate-height, input-responsive plant type by crossing indica and japonica types (Wang Huaqi et al, this volume).

Although cultivars with the *sd1* gene are particularly sensitive to water deficit at flowering, tall types also show high sensitivity at that stage. Rice generally responds to unfavorable conditions near flowering (low radiation, water stress, low N, etc.) by greatly reducing the number of reproductive sinks (Horie et al 1997). This pruning of sinks results in the fairly stable individual grain weight that characterizes lowland rice. In many cases, substantial amounts of nonstructural carbohydrates accumulate in the culms and leaf sheaths of rice toward the end of grain filling, indicat-

Table 4. Rice traits considered adaptive in the wild but counterproductive for modern intensive irrigated agriculture.

Trait	Value in the wild	Drawback for modern agriculture
Asynchronous flowering	Drought avoidance, outcrossing	Inefficient harvesting
Tall stature	Competitiveness, pollen/seed dispersal	Low harvest index, lodging
Genetic polymorphism	Adaptability to changing biotic and abiotic stresses	Variable harvest date, variable grain quality, variable year-to-year performance
Seedling vigor	Early aboveground resource capture, shading of competitors	Excessive early competition in monoculture
Variable dormancy of seeds	Some seeds germinate when conditions are favorable	Uneven seed germination
Deep roots	Drought tolerance	Associated with poor tillering, poor response to late-season fertilizer

ing that photosynthetic supply exceeded sink capacity. For perennial ancestral species, later tillering could compensate for the reduction in sinks on a given tiller, but, in annual aerobic rice, staggered maturity is not acceptable.

- *Implications for aerobic rice*

Aerobic cultivars need to combine adequate tiller number, early weed competitiveness, and input responsiveness. The *sd1* gene may be less suitable for this system; therefore, other sources of short stature and lodging resistance need to be considered. The severe reduction in sinks that occurs with mild stress near flowering should be moderated to allow a more "optimistic" strategy of maintaining more spikelets despite less favorable conditions. This may require a reduced sensitivity of stress perception for aerobic rice.

Molecular approaches

The complete sequence of the *Arabidopsis* genome (Arabidopsis Genome Initiative 2000) and draft sequences of the rice genome (Barry 2001, Goff et al 2002, Sakata et al 2002, Yu et al 2002) are now available to facilitate the discovery of genes underlying key agronomic traits, including those important for breeding aerobic rice. Particularly interesting are the reports clarifying the molecular basis of the key alleles underlying the breeding programs responsible for the Green Revolution. The *sd1* dwarfing allele corresponds to a mutation that inactivates GA20 oxidase-2 in the GA_3 biosynthesis pathway (Sasaki et al 2002, Spielmeyer et al 2002). In contrast, the wheat dwarfing gene *Rht-B1/Rht-D1* and the maize dwarf-8 (*d8*) gene are orthologues of the *Arabidopsis gibberellin insensitive* (*GAI*) gene (Peng et al 1999). *GAI* encodes a protein that resembles nuclear transcription factors and contains an SH2-like domain, indicating that phosphotyrosine may participate in gibberellin signaling.

Plant genome programs provide essential insights into the multiplicity of genes and their overlapping and contrasting patterns of expression. It is now clear that *sd1* affects GA_3 levels only in certain tissues because other tissues express the distinct but functionally related GA20 oxidase-1 gene (Sasaki et al 2002). Mutations in single-copy genes are likely to have pleiotropic effects in many tissues and may produce phenotypes that overall are unacceptable in a breeding program, whereas a mutation in one gene of a multigene family may have tissue-specific and/or quantitative effects that allow breeders to achieve a desired trait.

As mentioned above, the current ideotype of an aerobic rice cultivar is that it should combine certain traits found in germplasm adapted to the irrigated environment with other traits found in upland germplasm. Adequate tillering, high harvest index, and input responsiveness of irrigated cultivars would have to be combined with early weed competitiveness and tolerance of continuous mild water deficit of upland cultivars. To combine these traits, a breeder would have to overcome the potential antagonisms between them. For example, it would be necessary to minimize the tendency for tillering to decline under drought stress (Boonjung and Fukai 1996) or in a deep-rooted plant (Yoshida and Hasegawa 1982). Superficial roots that are ideal for absorption of late-season fertilizer inputs under irrigated conditions may have to be replaced by somewhat deeper but highly absorptive roots to survive aerobic conditions. Harvest index would have to be made less sensitive to drought stress through enhanced drought tolerance at both the vegetative and reproductive stages to ensure high dry matter accumulation and its preferential allocation to grain (Blum 1998). Discovery of the genes, pathways, and regulatory networks underlying the above traits would greatly aid the breeding program.

The potential entry points into gene discovery for such traits are numerous, but they can be grouped into three main types. The first type of entry point is mutational—using deletions or insertions to knock out or modify genes underlying traits. Insertional mutants are the most convenient because the inserted DNA tags the mutated gene. The second is map-based—using segregating populations to locate major genes and QTLs for the trait in question on the rice genetic map. For every 1 cM of genetic distance between flanking markers and the gene or QTL, there are 25–50 genes on the genome. Microarray analysis of the 250–500 genes in a 10-cM segment of the genome can provide information about gene expression patterns that will reduce the number of candidate genes considerably. Further reduction may come from an analysis of the probable coding function of the remaining genes. The third type of entry point is biochemical or physiological—using an understanding of the mechanisms underlying the traits to suggest candidate genes that can be queried using microarray analysis and reverse genetics. Bennett and Khush (2002) discuss the integration of these three approaches and their application to breeding rice with enhanced salt tolerance. Similar applications are anticipated for enhancing drought tolerance or adaptation to aerobic growth conditions.

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Developing and testing rice varieties for water-saving systems in the tropics

G.N. Atlin and H.R. Lafitte

The principal breeding target environments for water-saving systems are likely to be (1) near-saturated (NS) systems, in which rice is grown in nonflooded fields where soils are usually kept saturated, but occasionally dry to field capacity or below; (2) aerobic systems where rice is direct-seeded in nonpuddled, nonflooded fields in which soil moisture status is usually at or below field capacity. There is evidence that selection can be effective in both regimes, and that the requirement for a separate screening program for any irrigation regime is closely related to the difference in mean yield between the new target regime and standard management. NS systems are likely to exhibit only slight yield reductions relative to conventionally irrigated management and are therefore unlikely to require cultivars that are radically different from current elite irrigated varieties. The most efficient strategy for identifying cultivars for NS systems is therefore to screen short-duration, elite irrigated varieties under NS management to eliminate cultivars that are particularly susceptible to episodes of soil drying. Aerobic systems, which produce mean yields intermediate to those of irrigated and conventional upland management, are likely to require cultivars that have been selected from early generations under high-input aerobic management to produce genotypes that combine moderate tolerance of moisture stress with high harvest index and lodging resistance. Cultivars that perform well under aerobic management usually contain germplasm from both traditional upland and elite irrigated parents, but some cultivars without elite irrigated high-yielding variety parentage and some developed for irrigated systems also produce high yields in aerobic systems.

Water shortages for rice irrigation are driving the development of production systems designed to use less water. Adapted cultivars are proving to be a critical component of these systems (Guimarães and Stone 2000, Wang and Tang 2000). In devising breeding strategies for water-saving systems, as for any new breeding objective, we must first clearly define the target environment (TE), identify appropriate germplasm for introduction or use as parents, and develop screening methods that predict genotype performance in the TE (Atlin 2001). The objective of this paper is therefore to attempt to answer the following questions for tropical water-saving systems:

1. What are the main TEs to be examined by the breeding program, and what are the main features needed in cultivars for each TE?
2. Which TEs require separate breeding programs, and which can be served simply by screening material from existing programs under water-saving management?
3. What type of germplasm is likely to contribute the features required for each TE?
4. For each TE, how should screening be conducted?

The two principal TEs for breeding will be discussed below. Traits important for these environments, promising germplasm for use as parents, and effective approaches to screening are described.

Target environments for water-saving varieties

IRRI research on water-saving technologies for rice production focuses on two main approaches. One involves reducing water use in conventional irrigated rice systems through such techniques as alternate wetting and drying, saturated soil culture, and the use of raised beds. These management techniques save water by periodically allowing standing water to disappear from the field without replenishment, or by reducing the proportion of the field that is flooded, but they are designed to maintain paddy soil at or near saturation throughout the growing season. In these systems, termed in this paper *near-saturated (NS) systems*, soil is usually puddled, crops are usually established via transplanting, and roots grow in a mainly anaerobic environment. IRRI and other organizations are also developing aerobic production systems in which crops are direct-seeded in free-draining, nonpuddled soils and moisture content is maintained below saturation and may fall below field capacity. In these systems, roots grow in a mainly aerobic environment. NS systems offer relatively limited water savings but are likely to achieve yields close to those obtained in fully flooded systems. Aerobic systems offer the potential to greatly reduce water use, but currently have significantly lower yield potential than conventional irrigated systems.

Near-saturated systems

NS systems attempt to keep the root zone saturated or nearly so throughout the growing season, and thus expose rice crops to only limited levels of moisture stress. Because the soil environment differs only modestly from that of a flooded rice field, it is unlikely that separate breeding programs are needed for systems in which a flood is not maintained but soil is kept saturated. The conclusion that there is little need for a separate breeding program for NS systems is supported by a substantial body of evidence indicating that cultivar effects for grain yield tend to be highly correlated across irrigation regimes, unless the comparison is made between irrigation levels that result in a mean yield difference of 50% or more. For example, in a population of doubled-haploid lines, the phenotypic correlation between lowland yield and aerobic yield was highly significant when the aerobic yield was 56% of that of the lowland yield (Lafitte et al 2002). This correlation was weaker when water supply resulted in a greater yield reduction, and the correlation was not significant once the upland yield dropped below 30% of the lowland yield. Table 1 summarizes other experiments demonstrating a positive and usually high genetic correlation across irrigation regimes. In general, it appears that a reduced irrigation regime need only be considered a separate breeding target, for which an independent breeding program is required, if mean yields are substantially reduced by it. This is unlikely to be the case for most NS production systems. However, although separate germplasm development programs are probably not needed for conventional and NS irrigated systems, it seems likely that screening of cultivars developed for other systems under NS conditions will be useful to eliminate varieties that are extremely susceptible to soil drying. Screening elite lines under NS conditions to identify those that are particularly tolerant of mild, intermittent moisture stress is likely to be an efficient strategy for identifying germplasm adapted to water-saving irrigation systems.

Aerobic systems

There is strong evidence that high-input aerobic systems require specially bred cultivars that differ from both conventional upland varieties and elite irrigated varieties. In aerobic production systems, the crop is likely to experience higher levels of water stress before irrigation than usually occur in saturated or near-saturated culture. Thus, aerobic rice varieties need to be more tolerant of drought stress, particularly at the sensitive reproductive stage, than most irrigated varieties, and aerobic breeding programs must emphasize drought tolerance. Physiological and anatomical traits that may be required to maintain plant water status under mild to moderate drought stress

Table 1. Repeatability (*H*) of grain yield estimates in well-watered and moisture-stressed treatments, and genetic correlations across stress levels (r_G) in four trials evaluating random doubled-haploid lines derived from the cross CT9993-5-10-1/IR62266-42-6-2.

Location	Year	Season	Treatment	Mean yield	*H*	r_G	Data courtesy of
Bet Dagan,	1997	Wet	Control	164 g plot^{-1}	0.63	0.35	A. Blum
Israel			Stress	43 g plot^{-1}	0.81		
Coimbatore,	1999	Wet	Control	139 g plot^{-1}	0.56	0.86	R. Chandra Babu
Tamil Nadu			Stress	43 g plot^{-1}	0.60		
Paramakudi,	2000	Wet	Control	94 g plot^{-1}	0.23	0.91	R. Chandra Babu
Tamil Nadu			Stress	39 g plot^{-1}	0.76		
Ubon	2000	Wet	Control	2.02 t ha^{-1}	0.54	0.71	G. Pantuwan
Ratchathani			Stress	0.61 t ha^{-1}	0.50		

are reviewed by Lafitte and Bennett (this volume) and include traits that confer the capacity to explore a larger volume of soil for water, reduce cuticular water loss, and maintain leaf growth and transpiration at soil moisture levels between saturation and field capacity. Screening systems for aerobic rice should not select directly for these traits, but they will be favored in aerobic screening environments.

Aerobic rice production also constitutes a separate target environment from traditional upland rice-based systems. Most conventional upland cultivars developed for these systems are tall, have few tillers, and often produce low but stable yields under infertile conditions. They have low harvest indices and tend to lodge under favorable conditions, and are thus not suited to high-input management. However, improved upland-adapted rice varieties have been developed by IRRI and other breeding programs (Wang 2000, Guimarães and Stone 2000) that have adequate lodging resistance for production under high-input conditions and partition more dry matter to grain than traditional upland cultivars. Such varieties tend to be favored in national upland rice varietal release testing programs that emphasize selection for high yield in favorable environments, and, in tropical Asia, may be found among upland rice cultivars developed and released in the Philippines and India. The importance of the ability to increase dry matter partitioning to grain under optimal conditions has been observed in experiments at IRRI, where a set of 40 traditional and improved upland rice varieties has been screened in a broad range of environments and management regimes, ranging from high-input irrigated environments through favorable uplands to low-input, acid upland environments. The performance of an improved "conventional" upland variety, IR60080-46A, and a high-yielding aerobic rice variety, CT6510-24-1-2, is compared in Figures 1 and 2, in which the mean yield and harvest index

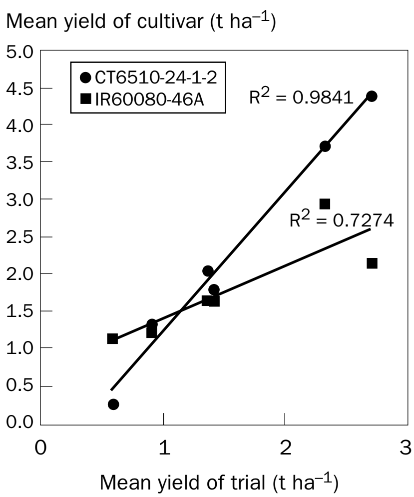

Fig. 1. Yield of a conventional (IR60080-46A) and high-yielding upland rice variety (CT6510-24-1-2) plotted against mean yield of six trials conducted over three seasons at IRRI and Siniloan.

(HI), respectively, are plotted against the mean of the experiment. The high-yielding aerobic variety CT6510-24-1-2 was able to partition a larger proportion of dry matter to grain under optimal conditions than was IR60080-46A, although the latter had a higher HI under less productive conditions.

Conventional upland rice varieties adapted to low-yield environments also lack the straw strength needed for high-input management, and, like B6144-MR-6-0-0, an excellent variety for infertile and weedy conditions, may lodge completely under fertile, well-watered conditions (Table 2). The need for very high HI and lodging resistance under highly fertile conditions is the key difference between aerobic and conventional upland systems in terms of cultivar requirements.

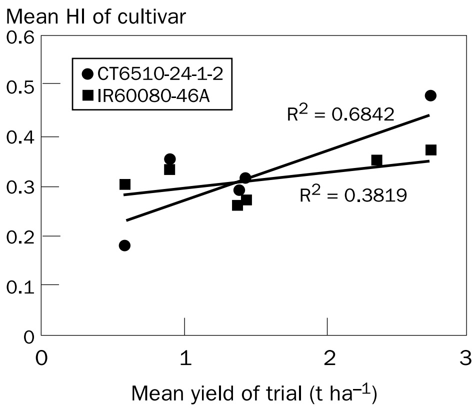

Fig. 2. Harvest index (HI) of a conventional (IR60080-46A) and high-yielding upland rice variety (CT6510-24-1-2) plotted against mean yield of six trials conducted over three seasons at IRRI and Siniloan.

Table 2. Agronomic performance of five varieties grown at IRRI under high-N management with twice-weekly sprinkler irrigation in the dry season of 2001 (harvested area = 5.75 m^2 $plot^{-1}$).

Cultivar	Grain yield ($t\ ha^{-1}$)	Height (cm)	Lodging (%)	Days to 50% flowering
Magat	4.27	80	0	83
IR55423-01	3.54	111	0	80
Maravilha	3.04	113	1	72
KMP 34	2.98	81	0	77
B6144	2.50	116	96	75
LSD[a]	0.72	6	–	3

[a]LSD = least significant difference.

Because of the requirements for moderate drought tolerance on the one hand and for high levels of responsiveness to fertilizer on the other, aerobic systems need to be considered separate breeding targets from both conventional upland systems and high-input irrigated systems.

Germplasm for water-saving systems

Germplasm for near-saturated systems

It is likely that high-yielding varieties for NS systems will be found among high-yielding irrigated varieties. As noted above, cultivar × irrigation regime interactions are limited across regimes that do not induce very large differences (approximately 50%) in mean yield. However, it is also likely that certain varieties are more tolerant of short periods of unsaturated conditions than others. Some irrigated varieties that are widely adopted in rainfed rice production regions, such as IR36, appear to exhibit this characteristic (G.S. Khush, personal communication). In general, a variety adapted to NS management is likely to be a fertilizer-responsive high-yielding variety developed for irrigated or favorable rainfed lowland conditions, but tolerant of soil drying. In northern India, where light soils can lead to occasional loss of saturation in irrigated rice fields, farmers have already identified certain varieties that are much less affected by bed planting or by short periods of drainage (Bouman et al, this volume). A critical trait for water savings is short duration. Water use for land preparation is fixed, but water use during crop growth is proportional to duration. Potential water savings resulting from reduced duration are nearly proportional to the reduction in the growth period. Although there is a yield penalty associated with very short duration, this penalty is not usually observed in tropical cultivars unless they are less than about 100 days in duration, whereas most elite irrigated cultivars have durations of 110–130 days. Thus, a water savings of approximately 10% is possible simply through the development of short-duration cultivars.

Germplasm for aerobic systems

A wide range of germplasm is potentially useful for aerobic systems. Some varieties developed for irrigated systems can produce very high yields under aerobic management. For example, the hybrid variety Magat, developed for irrigated production, is one of the highest-yielding cultivars yet identified at IRRI for high-input aerobic management in favorable conditions (George et al 2002). Under direct-seeded aerobic management, Magat often outyields pure lines with high yield potential by about 10–20% in trials, with means above 3.5 t ha^{-1} (Table 3). Magat maintains a high harvest index under aerobic conditions, whereas other irrigated cultivars do not (George et al 2002). However, most varieties performing well under aerobic management have been developed specifically for favorable upland environments. In both northern China and Brazil, where aerobic rice production systems depending on supplemental irrigation have been widely adopted by farmers, aerobic rice cultivars with high yield potential and moderate tolerance of moisture stress have been developed through crosses of traditional upland varieties with improved irrigated varieties (Guimarães and Stone

Table 3. Coefficients of coparentage of selected irrigated and input-responsive, lodging-resistant upland cultivars.

Cultivar	UPL-RI7	CT6510-24-1-2	IR64	IR72	IR8
IR55423-01	0.10	0.02	0.13	0.16	0.24
UPL-RI7		0.01	0.07	0.08	0.09
CT6510-24-1-2			0.02	0.02	0.03
IR64				0.08	0.31
IR72					0.34

2000, Wang and Tang 2000). Varieties combining high yield potential, high harvest index, lodging tolerance, and tolerance of moderate levels of moisture stress have also been developed for favorable rainfed upland environments in the tropics. These varieties tend to be preferentially selected by upland cultivar testing systems in many Asian countries because cultivar release decisions are usually made on the basis of official trials that are located in favorable moisture environments, fertilized heavily, and kept weed-free. This type of management is not very effective in selecting varieties that perform well under low-input management, but has resulted in the somewhat inadvertent development of several cultivars that are immediately suitable for aerobic rice production.

High-yielding cultivars that have emerged from Asian breeding programs for the favorable uplands are often rather closely related to elite tropical irrigated varieties, usually through IR8 and its relatives. For example, examination of the pedigree of the upland rice variety IR55423-01, one of the highest-yielding pure-line varieties under aerobic management in trials at IRRI, shows that its coefficient of coparentage with IR8 is only slightly less than that of the irrigated varieties IR64 and IR72 (Table 3). IR55423-01 does not, however, harbor the *sd-1* allele from its irrigated parents, and is of intermediate height. High-yielding upland indica lines such as IR55423-01 are characterized by moderate harvest index (about 35%), fairly stable biomass accumulation before flowering, and moderate panicle number (about 300 panicles m^{-2}; Lafitte et al 2002). The high-yielding Brazilian aerobic cultivars are also characterized by moderate tillering (250 tillers m^{-2}; Pinheiro and de Castro 2000). Panicle number is a feature that distinguishes these lines from irrigated semidwarf cultivars such as Magat and IR72, which produce more than 700 panicles m^{-2} in aerobic experiments (George et al 2002). Other successful upland-targeted cultivars have been derived from distinctly different genetic backgrounds from those of irrigated cultivars, and these have also achieved very high yields under high-input aerobic management at IRRI. For example, the line CT6510-24-1-2, another high-yielding line under high-fertility conditions and primarily of tropical japonica backgound, has very little relationship with the elite irrigated germplasm, indicating that a range of upland-adapted materials may be appropriate for use in aerobic systems. The IRRI aerobic rice breeding program is routinely screening elite irrigated, rainfed lowland, and upland varieties for performance under high-input management. The superior plant type in terms of height and tiller number for yield in aerobic systems is not yet known, so a range of plant types is being evaluated.

Effective approaches to screening germplasm for water-saving systems

The most effective approach for the identification of cultivars adapted to any target environment is usually to screen directly for performance in that environment, unless the repeatability (*H*) of grain yield estimates in the target system is low (Atlin 2001). In rice, *H* of grain yield estimates in variety trials does not appear to be much affected by soil water status per se, although uneven application of irrigation water to the experimental field can greatly increase error variances and reduce precision. For example, in a series of experiments in which random doubled-haploid lines from the cross CT9993-5-10-1/IR62266-42-6-2 were screened in contrasting irrigation regimes in four different environments, no consistent effect of soil moisture status was observed on *H* of grain yield, although yields were reduced by two-thirds in all stress treatments relative to the well-watered control (Table 1). These results indicate that direct selection in any irrigation regime is likely to be effective in increasing grain yield in that regime.

The positive genetic correlation usually observed across irrigation regimes (e.g., Table 1) also indicates that some of the gains resulting from selection at one moisture stress level will be expressed under other, similar stress levels. In general, the degree of correlation across stress levels is likely to be associated with the mean yield difference across irrigation regimes. This observation has important implications for screening and choice of germplasm to evaluate. For NS systems in which yield is reduced only slightly relative to that of conventional irrigated systems, the most effective approach is likely to be to select initially for yield potential under irrigated conditions, and then to screen high-yielding irrigated varieties for performance under the NS irrigation regime. In aerobic systems, the situation is more complex. Yield in high-input aerobic systems is currently about 30% lower than under conventional irrigated management, and at least 100% greater than yield in conventional low-input upland systems, which average 1–2 t ha^{-1} because of the lower yield of aerobic systems. Direct selection under high-input aerobic management from the earliest stages of a breeding program is therefore likely to be required to maximize selection response. Early screening of breeding lines under high-fertility aerobic management is particularly important in selecting for lodging resistance, a key trait for aerobic cultivars.

Conclusions

Large savings in water used for rice production are possible in tropical Asia through the use of NS and aerobic production systems. NS systems are likely to be optimized through the use of short-duration, elite irrigated cultivars that have been screened for tolerance of short periods of soil drying. Yields under NS management are likely to be reduced only slightly relative to those of conventional management, and therefore it is probably not necessary to mount a separate breeding effort for the system. Of the two systems, aerobic production offers the largest potential water savings, but at present this comes with a substantial yield penalty. Optimization of aerobic systems will likely require the development of a new cultivar type combining moderate drought tolerance, high rates of tillering, high harvest index, and lodging resistance. Some cultivars of this type have already been developed by Asian upland rice breeding programs, and these have a yield potential of more than 5 t ha^{-1} under high-input upland management. For both NS and aerobic production systems, screening should focus on direct selection for grain yield in conditions representative of the target environment. Screening for performance in these systems is under way at IRRI, and it is expected that a new generation of improved cultivars for both NS and aerobic systems will be available for tropical Asian rice producers in three years.

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Irrigation systems

Field-level water savings in the Zhanghe Irrigation System and the impact at the system level

R. Loeve, B. Dong, and D. Molden

The demand for freshwater from cities, industries, and environmental uses is growing rapidly throughout Asia. Less water will be available for agriculture and for rice in most places, yet more rice will be needed to feed a growing population. The per capita freshwater availability in China is among the lowest in Asia and it is becoming increasingly difficult to develop new freshwater sources. Much of the water will have to come from water savings—and rice, a water-intensive crop, is a major target for such savings.

On-farm water-saving practices, such as alternate wet and dry irrigation (AWDI), have been developed to reduce irrigation application requirements and to improve growing conditions, thereby increasing yield. However, the question is, If these practices have led to "real" water savings, which can be transferred to other agricultural and nonagricultural uses?

This paper explores water savings and water productivity on different scales to see if and how field-scale interventions scale up to subbasin-scale water savings in the Zhanghe Irrigation District (ZID) in Hubei Province, Central China. To study water savings and effects on different scales, the water-accounting procedure developed by IWMI was considered at four different spatial scales ranging from field to ZID.

Results show that at the field level, the water productivity per unit of irrigation water was much higher under AWDI than under the traditional methods because of lower irrigation water input. Farmers put much effort into making full use of irrigation water and rainfall.

Moving up the scales, other land uses gain more importance. Apparently, a certain size of scale is needed to have an impact from reuse of water, which becomes evident only at the main canal command scale, where the water productivity per unit of irrigation increased dramatically and almost all water is used within the domain. It becomes clear that the ZID, with its possibilities of capturing rainfall and runoff in all the reservoirs with the system, is very effective in capturing and using water for productive use.

The scope for additional real water savings in the Zhanghe Irrigation District is limited. Only 12% of the combined rainfall and irrigation water releases flow out of the basin. A further reduction in drainage outflow from the ZID may have negative downstream effects.

The results clearly indicate that scale effects are important for understanding and planning for water savings and water productivity.

Growing more rice with less water is one of the major challenges of the 21st century. Rapidly increasing water demands from cities, industries, and environmental uses will put a strain on water resources in many river basins. Yet, more rice will be needed to feed a growing population. The per capita freshwater availability in China is among the lowest in Asia and is still declining and it is becoming increasingly difficult to develop new freshwater sources. Much of the water needed has to come from water savings—and rice, a water-intensive crop, is a major target for such savings.

Major efforts have already been made to save water in irrigated rice areas and there is much to learn from previous efforts, particularly in China, where research and practices are well advanced. Many practices have been developed for farmers to deliver less water to their fields and these are collectively known as water-saving irrigation practices (Wang 1992, Mao 1993, Peng et al 1997), such as alternate wet and dry irrigation (AWDI), which has spread in South China (Li et al 1999). This practice is being implemented on a large scale in the Zhanghe Irrigation System (ZIS). A question of global interest is whether this practice has led to "real" water savings that can be transferred to other agricultural and nonagricultural uses.

The objectives of this paper are to (1) quantify the water productivity under AWDI and non-AWDI practices and (2) quantify the water productivity at different scales ranging from the field scale to the subbasin scale to get a better understanding of the "scaling up" of field-level water-saving practices. With this knowledge, important insights into the design and management of irrigation are gained that will lead to transferable water savings.

Methodology

Scales and water saving

As extensively described in Dong et al (2001), the term "water saving" has different meanings to different people at different scales. Farmers would typically like to make some more money from their resources and, if they have to pay for water, either by paying energy costs or costs of a service provider, they may have sufficient incentive to apply less water. At the farm level, "water saving" most often refers to a reduction in irrigation water applied to crops (Tuong and Bhuiyan 1999).

In many (water-short) river basins of the world, demand is growing for good-quality water for nonagricultural uses—the environment, cities, and industries. In these situations, irrigated rice agriculture is a relatively low-valued use of water and there is pressure to meet other demands first and then let agriculture have the remaining water. At the basin scale, a common interest is reducing the total amount of water depleted by irrigated agriculture while maintaining or increasing the production and transfer of water to other higher-valued uses.

However, water-saving practices at the field scale, with the objective of reducing supplies to fields, do not necessarily lead to transferable savings at the basin scale. At the basin scale, factors such as recycling of water (especially where rice is a major crop) and interaction of nonagricultural uses with water use for rice play a major role. For this research, four different scales were selected: field scale, mezzo scale, main canal command scale, and subbasin scale.

Subbasin scale: the Zhanghe Irrigation District

The ZID is situated in Hubei Province in Central China, north of the Yangtze River. This area is one of the most important bases of commodity grain in Hubei Province. The ZIS is one of the typical large-size irrigation systems in China, with a total area of 5,540 km^2, of which about 160,000 ha are irrigated area.

The Zhanghe reservoir, built on a tributary of the Yangtze River, supplies most of the irrigation water to the ZIS. The reservoir was designed for multipurpose uses of irrigation, flood control, domestic water supply, industrial use, and hydropower generation. In the ZIS, the canal systems include one general main canal, five main canals, and many branch canals with a total length of more than 7,000 km and more than 15,000 structures. Besides these, there are tens of thousands of medium- or small-sized reservoirs, small basins, and pump stations in the area partly incorporated into the system but sometimes operating independently. Downstream of the ZID is Chenghu Lake, which captures drainage flows from the ZIS.

The main crops are rice, winter wheat, sesame, and soybean, with paddy fields occupying about 80% of the total irrigation area. Figure 1 shows a layout of the ZIS within the ZID. For the research, the ZID is considered as the subbasin scale.

Main canal command scale

Although there are five main canals in the ZIS, only four of them are considered in this research, since satellite image data for a part of the fourth main canal command area were not available. The canal commands of the west main canal and first main canal are relatively small and both canal commands are considered as one. The second main canal and third main canal command area, including the Tuanlin pilot area, are considered separately.

No detailed maps were available that indicated the canal command boundaries. To define these boundaries, a combination of a digital elevation model (resolution 1 km × 1 km), the panchromatic band of Landsat 7 ETM+ of 10 July 2000 (resolution 15 m × 15 m), and topographic maps, including the canal layout, were used. Obviously, the main canal command scale does not refer only to the cultural (irrigated) command area of a canal system.

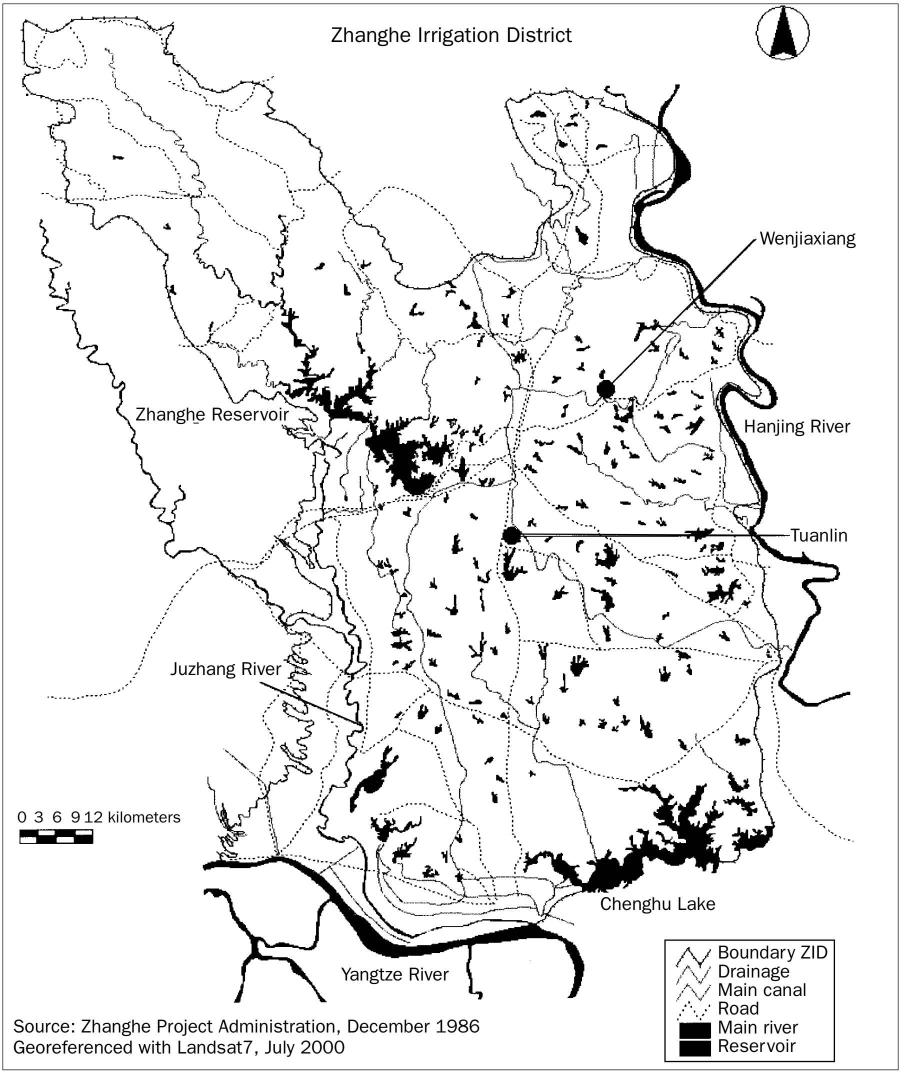

Fig. 1. The Zhanghe Irrigation System within the Zhanghe Irrigation District.

Mezzo scale

The two sites representing this scale are the Tuanlin and Wenjiaxiang pilot areas. The Tuanlin pilot area represents a situation where AWDI is said to be widely practiced and is located about 20 km southeast of the Zhanghe reservoir (see Fig. 1). The Tuanlin pilot area is irrigated by the first branch of the third main canal and a small-sized reservoir upstream. The total area is 287 ha, of which about 41% are paddy fields. The Wenjiaxiang pilot area represents a situation where AWDI is said to be not so common and is located about 35 km northeast of the Zhanghe reservoir (see Fig. 1). The Wenjiaxiang pilot area is supplied by the east branch of the fourth main canal and is located at the tail-end of the canal. The total area is 606 ha, of which about 28% are paddy fields. The northern part of the area is hilly and the elevation decreases gradually from north to south. The main crop at the two sites is middle rice that grows from the end of May to early September. Upland crops, such as maize and soybean, are also planted during the middle rice-growing season but they are normally not irrigated.

The landscape of the pilot areas consists of rice fields, trees, villages, roads, canals, drains, and many storage ponds. Water management practices and processes at this scale include allocation and distribution of water to farms, control of canal seepage, rainfall, runoff, and storage. Other nonagricultural uses influence overall water use. Within the mezzo scale, there is ample opportunity for reuse, but drainage outflow from the area also occurs. Downstream of the pilot areas is a medium-sized reservoir that captures all drainage flows. The source of water for the reservoir is the nonirrigated land that acts as a catchment area for the reservoir, plus any drainage water from rice fields. The reservoir is a supply for downstream agriculture plus cities and industries.

Micro scale

To represent this scale, three rice fields were selected in each of the two pilot areas, Tuanlin (AWDI) and Wenjiaxiang (non-AWDI), to capture the differences between on-farm irrigation water use of fields with and without AWDI.

Water accounting

The water-accounting procedure developed by IWMI (Molden 1997, Molden and Sakthivadivel 1999), based on a water balance approach, was used to study water savings. The water-accounting procedure classifies water balance components based on the outflow and on how the water is used. The water-accounting system was considered at the four spatial scales chosen to capture the scale effects of field-scale interventions. The water-accounting indicators are presented in the form of fractions and in terms of productivity of water and are explained in Box 1.

At the micro scale, the time period for water accounting was from land preparation (about 20 May) to 31 August. At the mezzo scale, the time period for water accounting was from land preparation (20 May) up to the end of harvesting (in 1999, 20 September, and in 2000, 10 September). At the main canal command area and subbasin scale, the time period for water accounting was from 15 April to 15 Septem-

Box 1. Water-accounting indicators and terminology (Molden 1997).

Gross inflow
The total amount of inflow crossing the boundaries of the domain. In this case, irrigation water, rainfall, and drainage water (we assume zero lateral groundwater flow).

Net inflow
Gross inflow less the change in storage over the time period of interest within the domain.

Committed water
The part of the outflow that is reserved for other uses such as downstream water rights or environmental uses.

Available water
The amount of water available to a service or use, which is equal to the inflow less the committed water.

Water productivity (WP)
The physical mass of production (rice) measured against irrigation inflow ($WP_{irrigation}$), gross inflow (WP_{gross}), net inflow (WP_{net}), process-depleted water ($WP_{ET\ (rice)}$), or available water ($WP_{available}$).

Depleted fraction (DF)
The fraction of gross inflow (DF_{gross}) or available water ($DF_{available}$) that is depleted by process and nonprocess uses (i.e., rice evapotranspiration and nonrice evapotranspiration, respectively).

Process fraction (PF)
The fraction of rice evapotranspiration over gross inflow (PF_{gross}), over total depletion ($PF_{depleted}$), and over available water ($PF_{available}$).

ber 2000 for evapotranspiration. For irrigation releases for the main canal commands, the period was from 1 April to 1 September 2000, since only monthly data were available for all the main canals. However, as daily data for the general main canal, first main canal, and west main canal show, no irrigation water releases occurred before 10 April 2000 and after 1 September 2000. For rainfall, the period of 1 May to 10 September 2000 was used.

Measurements

Land-use pattern. At the micro scale, the selected fields were cultivating rice and the area of the fields was measured. At the mezzo scale, the land-use pattern was determined with secondary data from the villages in the area. The total area was determined from a map and with help from remote sensing. At the main canal command area and subbasin scale, a satellite image (Landsat 7 ETM+, 10 July 2000) was used to create a land-use classification map. However, since the rice fields in the ZIS are small, the Landsat 7 ETM+ resolution (30 × 30-m thermal band) will not capture field canals, field roads, and rice field bunds. Therefore, a correction factor was applied to the rice area. A percentage of 5% for field canals, 5% for rice field bunds, and 4% for field roads is subtracted from the total area classified as rice.

Evapotranspiration. At the field and mezzo scale, the reference evapotranspiration (ET_0) was calculated with the Penman-Monteith equation (Allen et al 1998). All meteorological data for the ET_0 calculation were from the Tuanlin Irrigation Experiment Station. The meteorological data were manually observed thrice a day (at 0800, 1400, and 2000). Monthly averages were used as input for the ET_0 calculations. The actual evapotranspiration was calculated by multiplying the ET_0 by a crop coefficient. The evaporation from open water (ponds, canals) was calculated with pan-evaporation data from the Tuanlin Irrigation Experiment Station.

At the main canal command area and subbasin scale, the actual evaporation was estimated with the surface energy balance algorithm for land (SEBAL) developed by Bastiaanssen et al (1998). SEBAL is a thermodynamically based model, seeking to find energy-balance terms at the land surface. The practical procedures are extensively described in Chemin and Ahmad (2000) and Tasumi et al (2000). Chemin and Alexandridis (2001) describe in detail the procedure on how the actual evapotranspiration is calculated from NOAA AVHRR images acquired at various dates in the ZID and these images are used together with daily reference evapotranspiration data from the Tuanlin Irrigation Experiment Station. The result from the NOAA AVHRR images is a seasonal actual evapotranspiration map, which was merged with a Landsat 7 ETM+ image (image acquired on 10 July 2000) to redistribute the seasonal evapotranspiration to finer resolutions. The result is an improved local estimation of water consumption. However, since the rice fields in the ZIS are small, the Landsat 7 ETM+ resolution (30×30-m thermal band) will not capture field canals, field roads, and rice field bunds. Therefore, a correction factor was applied to the evapotranspiration from rice. A percentage of 5% for field canals and 5% for bunds is subtracted from the total evapotranspiration in the rice area and is then replaced by the corresponding area of evapotranspiration of natural vegetation observed in the canal command area when separating the evapotranspiration by land use. Field roads are assumed to be bare soil and 4% of the total evapotranspiration in the rice area was subtracted and then substituted by the equivalent area of bare soil evapotranspiration observed in the canal command. To validate the remote-sensing evapotranspiration data, a comparison was made between ET derived from remote sensing at the mezzo scale and ET derived from climatological data and land use at the mezzo scale. The results were very comparable and will be presented in Chemin et al (2002).

Rainfall. For the micro and mezzo scale, rainfall measurements were taken daily in both Tuanlin and Wenjiaxiang. For the main canal command and subbasin scale, monthly rainfall data from 23 stations were used. A representative area was attributed to each station with help from Thyssen polygons. The volume of rainfall was calculated by multiplying the area by the rainfall. Since none of the stations were located close to the boundary of the subbasin scale, the area attributed to the stations the closest to the boundary was big. This might lead to less accurate rainfall volume data.

Surface water inflow and outflow. Inflow and outflow of surface water were measured at the boundaries of the study area (at both the micro and mezzo scale) twice a day. The discharge was measured using different measurement structures, such as broad-crested weirs, V-notch weirs, trapezoidal weirs, and pipes. In the main and branch canals, a current meter was used for the discharge measurements. In temporary inflow/outflow points, portable cutthroat flumes were installed. The operating time of several pump stations was recorded for discharge calculations. The discharge was converted to a water volume by multiplying the discharge by time. The volume divided by the area gives the inflow and outflow in millimeters. To calculate the irrigation duty (for rice) in millimeters for the mezzo scale, the volume of committed outflow (i.e., the part of the outflow that is committed to downstream uses) is subtracted from the total irrigation water inflow and divided by the rice area. At the main canal command area and subbasin scale, secondary data were collected on water releases to the main canals and from the Zhanghe reservoir.

Storage change. Storage change was calculated only in 2000 for (1) *soil moisture:* before land preparation and after harvesting, the soil moisture content in the top 30 cm of the soil was measured by the gravimetric method; (2) *surface water storage:* before land preparation and after harvesting, water levels in selected ponds were measured and multiplied by the total area covered by the ponds; and (3) *groundwater storage:* before land preparation and after harvesting, the water levels in four wells at each site were measured. The groundwater volume was calculated by multiplying the water level by the specific yield of the soil (estimated specific yield 0.10).

Water levels in fields. The water levels in the selected fields were measured to assess whether AWDI was prevalent in an area. The water levels were monitored daily and measured in 1999 with an open-bottom lysimeter and a plastic tube; in 2000, the lysimeter was replaced with simple wooden sticks.

Yield. For the micro scale, yield data were obtained from a crop cut of 6 m^2 in the field. For the mezzo scale, yield data were obtained from a socioeconomic survey, which had a bigger sample size and better spatial distribution over the mezzo sites than the micro-scale yield data. For the main canal command and subbasin scale, remote sensing was used to calculate crop production. As described in Bastiaanssen and Ali (n.d.), a biomass growth map was produced from NOAA images. To improve the spatial distribution, a Landsat 7 ETM+ image was used. The nonrice areas were masked out using a land-use map. However, since the rice fields in the ZIS are small, the Landsat 7 ETM+ resolution (30 × 30-m thermal band) will not capture field canals, field roads, and rice field bunds. Therefore, a correction factor was applied to the biomass production in the rice area. A percentage of 5% for field canals and 5% for bunds is subtracted from the total biomass production in the rice area. Field roads are assumed to be bare soil and do not produce biomass. A harvest index value of 0.5 was used for biomass to rice production conversion. Rice production divided by rice area results in yield. To validate the remote-sensing yield data, a comparison was made between yield derived from remote sensing on the mezzo scale and from the socioeconomic survey. The results were very comparable and will be presented in Chemin et al (2002). Secondary data on crop production were also collected at the subbasin scale.

Results

Table 1 shows the water-accounting indicators on different scales presented separately.

Micro scale

As presented in Dong et al (2001), results from the Tuanlin Irrigation Experiment Station show that the water productivity per unit of irrigation water under alternate wet and dry irrigation is significantly higher (average 27%) than under traditional irrigation methods. However, the yield difference between the two methods is not statistically significant.

The actual farmers' practices show similar results although none of the farmers we monitored practiced a pure form of AWDI or traditional irrigation. The field water-level measurements show that farmers in Tuanlin practiced a form of irrigation much closer to the ideal AWDI practiced in timing of irrigation application, application frequency, duration, and depth of water application than in Wenjiaxiang. The water productivity values per unit of irrigation water are higher (up to 34%) under AWDI than under traditional irrigation methods (Dong et al 2001). The average water productivity per unit of irrigation in Tuanlin is 1.64 kg m^{-3} (see Table 1). In 1999 and 2000, rice yields in Wenjiaxiang (non-AWDI) were slightly higher than those in Tuanlin (AWDI).

The process fraction of gross inflow (PF_{gross}) indicates the amount of gross inflow that is depleted by rice ET. At the field scale, PF_{gross} ranged from 0.66 to 0.93 at both sites, indicating that much effort has been made to make full use of irrigation water and rainfall. Field observations indicate that farmers are quite effective in capturing and storing rain, even with traditional practices.

Mezzo scale

In 1999, the irrigation duty in Tuanlin (AWDI) was 29% less and in 2000 about 21% less than in the Wenjiaxiang (non-AWDI) mezzo site. The water productivity per unit of irrigation was consistently higher for Tuanlin in both years. However, it is much lower than at the field scale. On average, rice consumes 55% of the depleted water ($PF_{depleted}$) in Tuanlin and 42% in Wenjiaxiang. Rice covers about 41% of the Tuanlin mezzo site and 28% of the area at Wenjiaxiang. At the mezzo scale, other land uses such as upland crops and noncropped areas (trees, houses, roads, canals, ponds) play an important role.

The depleted fraction of gross inflow ranges from 0.09 to 0.20 for the two mezzo sites (Table 2), much lower than at the field scale. Drainage flows out of the mezzo areas include runoff from nonrice land plus drainage flows from rice fields. What happens to these drainage flows?

Following the nondepleted water (the outflow) downstream of the mezzo sites revealed that the outflow was captured and stored in a downstream reservoir that again supplied water to agriculture, cities, and industries downstream. The mezzo site is a catchment area for downstream reservoirs situated within the ZID. The role of

Table 1. Water-accounting indicators on different scales. See Box 1 for explanation of WP, PF, and DF.

Descriptor	Scales					
	Measurements		Remote sensing			
	Field[a]	Mezzo[b]	First main canal command[c]	Second main canal command	Third main canal command	Subbasin (ZID)
Total area (ha)	0.76	287	28,519	160,206	196,388	466,800
Rice area (ha)	0.74	117	5,373	44,577	62,060	126,086
Irrigation (mm)[d]	493	1,199	263	182	202	219
Irrigation (m^3) (000)	3.4	1,399[e]	14,140	81,266	125,592	275,729[f]
Rainfall (mm)	463	463	469	471	326	378
Rainfall (m^3) (000)	3.5	1,328	133,886	754,194	639,427	1,763,290
Gross inflow (mm)	956	5,100	733	653	528	596
Gross inflow (m^3) (000)	6.9	14,630	148,026	835,461	765,019	2,039,019
Storage change (mm)	–18	–5	0	0	0	0
Storage change (m^3)	–140	–13,655	0	0	0	0
Net inflow (mm)	938	5,095	733	653	528	596
Net inflow (m^3) (000)	6.8	14,617	148,026	835,461	765,019	2,039,019
Committed outflow (mm)	0	4,55	0	0	0	0
Committed outflow (m^3) (000)	0	11,634	0	0	0	0
Available water (mm)	938	1,040	733	653	528	596
Available water (m^3) (000)	6.8	2,714	148,026	835,461	765,019	2,039,019
ET (rice) (mm)	623	635	494	529	522	510
ET (rice) (m^3) (000)	4.6	741	26,539	235,804	324,092	642,749

continued on next page

Table 1 continued.

Descriptor	Scales					
	Measurements		Remote sensing			
	Field[a]	Mezzo[b]	First main canal command[c]	Second main canal command	Third main canal command	Subbasin (ZID)
ET (nonrice) (mm)	0	374	316	395	362	337
ET (nonrice) (m^3) (000)	0	637[g]	73,225	456,642	486,396	1,146,768
Total depleted (mm)	623	1,010	810	924	884	847
Total depleted (m^3) (000)	4.6	1,378	99,764	692,446	810,488	1,789,517
Production (t)	5.6	739	24,780	242,373	333,820	663,705
Yield (t ha^{-1})	7.4	6.3	4.6	5.4	5.4	5.3
Indicators						
WP gross (kg m^{-3})	0.81	0.05	0.17	0.29	0.44	0.33
WP net (kg m^{-3})	0.82	0.05	0.17	0.29	0.44	0.33
WP irrigation (kg m^{-3})	1.64	0.53	1.75	2.98	2.66	2.41
WP ET(rice) (kg m^{-3})	1.19	1.00	0.93	1.03	1.03	1.03
PF gross (rice)	0.67	0.05	0.18	0.28	0.42	0.32
PF available (rice)	0.68	0.27	0.18	0.28	0.42	0.32
PF depleted (rice)	1.00	0.54	0.27	0.34	0.40	0.36
DF gross	0.67	0.09	0.67	0.83	1.06	0.88
DF available	0.68	0.51	0.67	0.83	1.06	0.88

[a]Tuanlin, 2000, average of three micro sites. [b]Tuanlin mezzo site, 2000. Source Dong et al (2001). [c]The first main canal command is the aggregation of the first main canal and west main canal command. [d]Assuming only rice is irrigated. At the larger scales, only the releases from the main canals are taken into account and converted to application depth. Actual application depth will be higher because of reuse of water. [e]The volume of irrigation water is adjusted for the enormous amount of committed water flowing through the mezzo site. The irrigation diversion flowing into the area is a factor 10 bigger than the irrigation water available for the area. [f]The daily data on irrigation releases from the Zhanghe reservoir from 10 April 2000 (no earlier releases) to 1 September 2000 (no releases after) give a total volume of 301,184,562 m^3. The monthly values of all canals should add up to the total irrigation releases from the Zhanghe reservoir, but yields a volume of 250,273,156 m^3. The average number was used for further calculations. Possible reasons for this discrepancy are that the main canal administrations like to keep the total volume lower to pay less water fees to the Zhanghe reservoir, measurement inaccuracies, and seepage from the canal. [g]Of which nonbeneficial evapotranspiration (ET) is 412,451 m^3 and upland crop ET is 224,907 m^3.

Table 2. Water-accounting indictors at the mezzo scale in Tuanlin and Wenjiaxiang (Dong et al 2001). See Box 1 for explanation of DF, PF, and WP.

Indicators	Year 1999		Year 2000	
	Tuanlin	Wenjiaxiang	Tuanlin	Wenjiaxiang
DF_{gross}	0.13	0.20	0.09	0.20
PF_{gross}	0.09	0.08	0.05	0.08
$PF_{depleted}$	0.56	0.41	0.54	0.42
$WP_{irrigation}$ (kg m^{-3})	0.98	0.79	0.53	0.42
WP_{ET} (kg m^{-3})	1.04	1.72	1.00	1.01

these reservoirs within the ZID in capturing and reusing water should be reflected by the water-accounting indicators going up one scale to the main canal command scale.

Main canal command scale

Inflow into the main canal domain is either irrigation water releases from the Zhanghe reservoir or rainfall. It is assumed that there is no committed outflow from the main canal command scale since all irrigation water is specifically released for this particular command area. It is also assumed that, during the rice season, change in storage is small in comparison with other water-balance terms, and thus set at zero in our analysis. Therefore, gross inflow is equal to available water. Committed water to cities and industries is accounted for by the Zhanghe reservoir authorities, who label water releases as irrigation water or water for cities and industries.

As can be seen in Table 1, the water reuse on the main canal command scale is reflected in water productivity per unit of irrigation[1] values, which are three to almost six times as high as on the mezzo scale. However, to make a more accurate comparison between the scales, our Tuanlin mezzo site should be compared with the Third Main Canal command in which the Tuanlin mezzo site is located. Here we see that the water productivity per unit of irrigation is about five times as high as at the Tuanlin mezzo site. The marked increase across scales is because of the recapture and reuse of water by the reservoirs. At the mezzo scale, rainfall was not captured and entered the drain as runoff. At the larger scale, the rain was effectively captured and used.

The water productivity per unit of rice evapotranspiration remains almost the same (around 1 kg m^{-3}) since the rice plant still needs the same amount of water for production. There is some variability across space, but this indicator does not change across scale.

[1]At this scale, we consider the Zhanghe reservoir releases only as irrigation water as this is the water that crosses the boundary of the domain.

The process fraction of gross inflow increased from the mezzo scale. However, the process fraction of depleted water decreased. Other land uses such as upland crops and noncropped areas deplete an increasing amount relative to process uses at this scale. In the third main canal command, about 32% of the total area consists of rice compared with 41% at the Tuanlin mezzo scale.

The depleted fraction of gross inflow increased enormously to a bit more than one in the third main canal command. This indicates that either the water storage decreased (be it groundwater abstraction or soil moisture depletion) and was used for water consumption or measurement errors occurred in the inflow. In spite of uncertainties in the estimate, this large value indicates that most water is depleted within the area and not much outflow will be available for downstream use.

The first and second canal commands also have fairly high depleted fractions of gross inflow, but some outflow still occurs that can be used downstream. The subbasin scale will show how much water ultimately is used within the Zhanghe Irrigation District.

Subbasin scale (Zhanghe Irrigation District)

The boundaries of the ZID scale are taken as the Zhanghe reservoir upstream, the Juzhang River to the west, the Yangtze River and Chenghu Lake to the south, and Hanjing River to the east. As for the main canal command scale, storage change and committed outflow are assumed to be zero. Table 1 shows the water indicators at the subbasin scale. The water productivity per unit of irrigation water is 2.41 kg m^{-3}, lower than that of the second and third main canal command, but higher than that of the first main canal command. Also compared with the weighted average value of the three main canal commands (2.73 kg m^{-3}), there is a decrease. However, there is some uncertainty about the actual volume of water released for irrigation. If the added monthly values of all canals are taken as the total irrigation releases from the Zhanghe reservoir (250.3 million m^3), the value of the water productivity per unit of irrigation water will be 2.65 kg m^{-3}. This is almost equal to the values on the third main canal command scale, but still slightly lower than the weighted average of the three main canal commands. The water productivity per unit evapotranspiration remains the same (around 1 kg m^{-3}).

The process fraction of gross inflow decreased slightly from 0.35 (weighted average of the three main canal commands) to 0.32. This means that 32% of the gross inflow is consumed by rice. This is very much in line with the small decrease in rice area at the subbasin scale. At the subbasin scale, the rice area is about 27% of the total area and in the three main canal commands the rice area is about 29% (weighted average) of the total area. The process fraction of depleted water went from 0.36 to 0.37 (weighted average of the three main canal commands). The depleted fraction decreased from 0.93 (weighted average of the three main canal commands) to 0.88. So, only 12% of the inflow (irrigation and rainfall) is flowing out of the Zhanghe Irrigation District.

Water-accounting indicator trends over scale

The following figures illustrate the trends over scale of water productivity (Fig. 2), process fraction (Fig. 3), and depleted fraction (Fig. 4). To ensure that all scales are visible, a logarithmic scale was chosen for the area. However, this presentation has the limitation that the relative differences between scales (1 to 1,000 ha looks the same as 1,000 to 1,000,000 ha) are less obvious. For the main canal command scale, only the third main canal command is incorporated since this is the canal command where the Tuanlin mezzo site is located.

The water productivity trend over scale (Fig. 2) shows that the water productivity per unit of evapotranspiration stays just above 1 kg m^{-3} over all scales; only the value at the field scale is a bit higher, for which we have no explanation. There may be location-specific differences in this value, but there is no reason to expect that this value is scale-dependent.

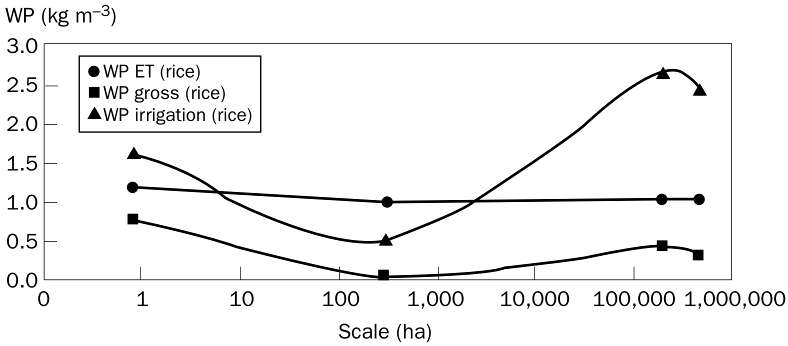

Fig. 2. Trends of water productivity (WP) per unit of gross inflow, irrigation inflow, and evapotranspiration over scale.

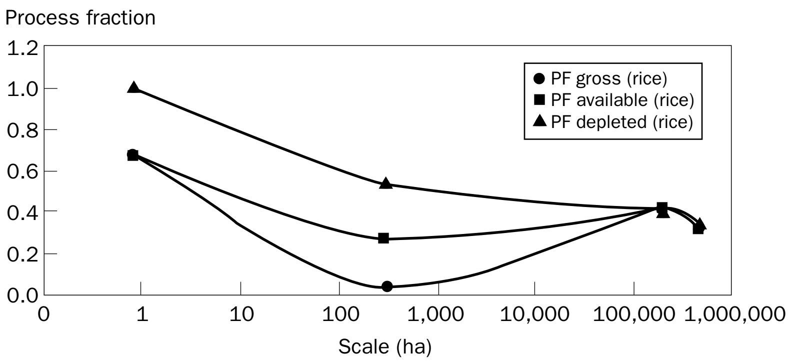

Fig. 3. Trends of process fraction (PF) per unit of gross inflow, available water, and depleted water over scale.

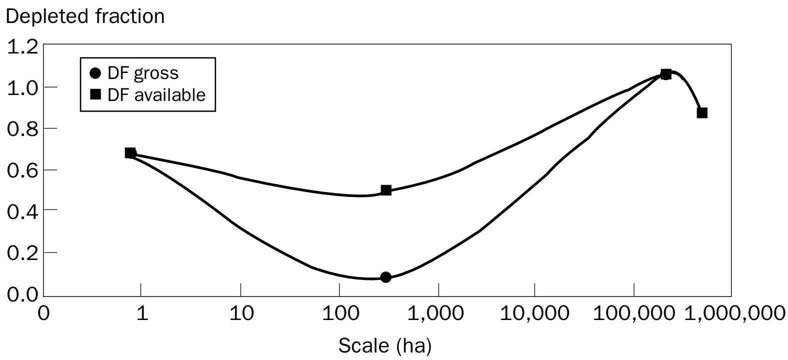

Fig. 4. Trends of depleted fraction (DF) per unit of gross inflow and available water over scale.

The water productivity per unit of gross inflow drops dramatically at the mezzo scale because of considerable (drainage) outflow from the domain. However, this outflow is captured again at the third main canal command scale and the value rises again. At the subbasin scale, there is a small drop again. Other factors apparently become important, such as runoff capturing of the natural vegetation. Because of lateral flows across scale domain boundaries, and recapture of this flow, the water productivity of gross inflow is scale-dependent.

The water productivity per unit of irrigation water is very high at the field scale where farmers are extremely cautious with the water they have to pay for. It decreases at the mezzo scale because of drainage out of the area and increases dramatically at the third main canal command scale because of reuse. Apparently, a certain size of scale is needed to have an effect from the reuse of water. At the subbasin scale, there is a slight decrease, but the value is much higher than at the field scale.

The process fraction trend over scale (Fig. 3) shows that the process fraction per unit of gross inflow at the field scale is very high, indicating that farmers have made much effort to make full use of irrigation water and rainfall. At the mezzo scale, the value of the process fraction per gross inflow drops dramatically to 5%. This is explained by the huge amount of outflow, which is used again at the main canal command scale, where the process fraction of gross inflow increased again. At the subbasin scale, a slight decrease occurs, which is in line with a slightly lower rice land use at this scale.

The process fraction per unit of depleted water shows a downward trend going up the scales. Other land uses such as upland crops and noncropped areas gain more importance when the scale becomes larger.

The depleted fraction of gross inflow trend over scale (Fig. 4) again shows a downward trend from the field scale, where farmers are quite effective in capturing and storing rain, to the mezzo scale, where much outflow reduces the DF_{gross} value. At the third main canal command scale, DF_{gross} increased enormously. It is striking that values close to 1.0 are achieved, meaning that farmers and water managers are extremely effective in capturing and depleting the water available to them. Most water is depleted within the area and not much outflow will be available for downstream use. A high value for the depleted fraction is often a danger sign for the environment. At the subbasin scale, the depleted fraction per unit of gross inflow decreases. There is not much scope for additional savings in the area by converting drainage outflow to more process depletion.

Discussion and conclusions

Results from the Tuanlin Irrigation Experiment Station and actual farmers' practices show that water-saving irrigation techniques such as alternate wet and dry irrigation reduce water deliveries to fields without significantly changing yield. Thus, water productivity per unit of water delivered to fields is higher with AWDI than with conventional practices.

The process fraction of gross inflow is very high and indicates that much effort has been made to make full use of irrigation water and rainfall. Field observations indicate that farmers are quite effective in capturing and storing rain, even with traditional practices.

At the mezzo scale, the water productivity per unit of irrigation was consistently higher for Tuanlin (AWDI). In both cases, though, the values of water productivity per unit of irrigation were much lower than at the field scale. The process fraction of depleted water decreased to 0.55 in Tuanlin and to 0.42 in Wenjiaxiang and the depleted fraction of gross inflow decreased dramatically compared with the field scale. At the mezzo scale, other land uses such as upland crops and noncropped areas (trees, houses, roads, canals, ponds) play an important role. Following the nondepleted water (the outflow) downstream of the mezzo sites revealed that the outflow was captured and stored in a downstream reservoir that again supplied water to agriculture, cities, and industries downstream.

At the main canal command scale, the water productivity per unit of irrigation (measured by the Zhanghe reservoir releases) is three to almost six times as high as on the mezzo scale because of effective rainfall capture and use at this scale, thus lessening the need for Zhanghe water. As expected, the water productivity per unit of evapotranspiration remains almost the same. The process fraction of gross inflow increased, which means that more rainfall plus irrigation was converted to rice evapotranspiration than at the mezzo scale. However, the process fraction of depleted water decreased because other land uses besides rice increased beyond values obtained at the mezzo scale. Other land uses such as upland crops and noncropped areas gain even more importance at this scale. In the third main canal command, the depleted fraction of gross inflow increased markedly to a bit more than one. This indicates that either the water storage decreased (be it groundwater abstraction or soil moisture depletion) and was used for water consumption or measurement errors occurred in the inflow. Certainly most water is depleted within the area and not much outflow will be available for downstream use. The first and second main canal commands also have fairly high depleted fractions of gross inflow, but some outflow still occurs, which can be used downstream.

At the subbasin scale, the water productivity per unit of irrigation water is lower than the second and third main canal command and the weighted average value of the three main canal commands. Again, the water productivity per unit evapotranspiration remained about the same. The process fraction of gross inflow decreased slightly, which is in line with the small decrease in rice area at the subbasin scale. The process fraction of depleted water remained similar. The depleted fraction decreased to 0.88, meaning that only 12% of the inflow (irrigation and rainfall) is flowing out of the Zhanghe Irrigation District.

When we look at the trends over scale of the different water-accounting indicators, it becomes clear that the water productivity per unit of evapotranspiration remains more or less the same over all scales. It is obvious that the rice plant consumes the same amount of water for reproduction whatever the scale is. All other indicators show a decrease at the mezzo scale because of considerable (drainage) outflow from the domain. However, all indicators, except the process fraction per unit of depleted water, show an upward trend when going to the main canal command scale. This is explained by the reuse of water. Here it becomes clear that the ZID with its possibilities of capturing rainfall and runoff in all the reservoirs within the system is very effective in capturing and using water productively. Apparently, a certain size of scale is needed to have an effect from the reuse of water.

All indicators show a decrease when scaling up from the main canal command scale to the subbasin scale. Other land uses such as upland crops and noncropped areas gain even more importance at this scale. This also becomes very clear in the trend of the process fraction per unit of depleted water, which shows a continuous downward trend going up the scales. Other land uses such as upland crops and noncropped areas gain more importance when the scale becomes larger.

Although the Yangtze basin is considered to be an open basin and inflow into the Yangtze can be considered as flow to a sink, since the water is not used downstream, the scope for developing new freshwater sources through water savings in the Zhanghe Irrigation District is limited. With only 12% of the rainfall and irrigation water releases flowing out of the basin, it is expected that the outflow cannot be further exploited without negative downstream effects on, for example, Chenghu Lake. The figures indicate that planners, designers, managers, and farmers have been quite effective in saving and using water in the ZID. This was accomplished by several strategies. Certainly at the farm scale, AWDI practices reduce the requirement for irrigation deliveries, thus allowing water to be stored in upstream reservoirs. Farmer practices also promote the capture and use of rain on their fields. The additional storage within the ZID clearly plays an important role in water savings. Drainage from fields, and more importantly runoff from nonrice land, is effectively captured for use within the system. Delivering limited volumes of water to farms and effectively managing reservoirs require sound canal operation and maintenance practices. Again, exemplary practices have been observed in the ZID and described in Loeve et al

(2001). Further improvements can be made in reducing costs of water delivery service and in improving the environment in the area.

In areas where water is severely limited, as in the third main canal command, there is no additional water to deplete, so the way to increase production is to increase the amount of kilograms per unit of crop evapotranspiration and reduce nonprocess evapotranspiration.

When focusing on increasing the water productivity per unit of irrigation, some caution is warranted. $WP_{irrigation}$ is highly dependent on rain. If a lot of rain occurs in one year, less irrigation water is required to achieve the same yield and the water productivity per unit of irrigation increases. Furthermore, in areas where there is considerable water reuse, as in the Zhanghe Irrigation District, a reduction in irrigation supplies at the field scale may or may not lead to an overall increase in productivity at the subbasin scale if the drainage water is reused downstream. However, if the field water savings could lead to a lower demand and the Zhanghe reservoir operators could keep the water stored high in the system, they could direct it to other more productive uses.

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Notes

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Modeling approaches to quantify the water balance in groundwater-dominant irrigation systems: an example of Rechna Doab, Pakistan

S. Khan, K. Ullah, E. Christen, and H.M. Nafees

Irrigated agriculture in alluvial basins is characterized by high seepage losses from rivers, channels, and irrigated fields to the aquifer systems. Water accounting at the farm or management unit level tends to underestimate the productive use of water since losses from the supply system can be reused for irrigation through downstream groundwater pumping. However, pumping can mobilize poor-quality groundwater and can cause an overall loss of good-quality water supplies. Increased groundwater pumping also increases seepage losses from irrigation channels and watercourses. This situation requires an understanding of spatial and temporal variation of surface-water and groundwater interactions and salt movements under variable scenarios of surface-water availability.

This paper describes details of hydrological studies in the Rechna Doab basin, Punjab, Pakistan. The basin has 3 million ha, of which 2.3 million ha are cultivated land with rice, cotton, and fodder crops dominating in the summer and wheat and fodder in the winter. A top-down nodal network was developed to determine the irrigation water balance for individual administrative units. The spatial groundwater recharge estimates obtained from the nodal network were used to check the water balance estimates from a more distributed bottom-up approach. The bottom-up approach used a distributed dynamic model that simulated surface-water and groundwater interactions at the desired level of interest. The distributed nature of the surface-groundwater interaction model enabled a performance assessment of individual administrative units by taking into account downstream beneficial use and quality variation of lost surface water. This water and salt balance approach highlighted the need for integrated management of surface water and groundwater from the administration unit to the basin level.

In groundwater-dominant irrigation systems, crop water demands are conjunctively met by surface water and groundwater. While it is important to ensure efficient use of surface-water supplies (e.g., more grain per drop of water) by improved transmission and irrigation methods, this may cause reduced recharge to aquifers and hence lower availability of water to farmers relying on groundwater for agriculture. This problem requires a systems approach to determine the water balance at different scales as deep percolation losses from one administrative or hydrological unit may be reused in another unit (Rushton 1999, Seckler 1996). The water lost through deep percolation from one hydrological unit goes through geochemical changes before it becomes available as groundwater in another hydrological unit. This necessitates consideration of water-quality implications in the reuse of water in groundwater-dominant systems.

Water rights are often associated with administrative units irrespective of the hydrological interactions and boundaries of the system. This necessitates determination of water-use efficiency at each of the administrative units and how this contributes to the overall system efficiency. The quantitative assessment of water productivity or water-use efficiency requires a range of methodologies that can capture system water and salt dynamics at both the hydrological and administrative scales. This paper describes two approaches for understanding the role of both surface water and groundwater in meeting crop water demand at administrative and hydrological unit levels in Rechna Doab, Pakistan.

Description of study area

The Rechna "*Doab*" (land between two rivers) is the interfluvial sedimentary basin of the Chenab and Ravi rivers in Pakistan (Fig. 1). It lies between longitude 71°48′ to 75°20′ E and latitude 30°31′ to 32°51′ N. The gross area of Rechna Doab is 2.97 million ha, with a longitudinal extent of 403 km and maximum width of 113 km, and it contains 2.3 million ha of prime cultivated land. It is one of the oldest, agriculturally richest, and most intensively populated irrigated areas of Punjab, Pakistan.

The flows of the Chenab and Ravi rivers bounding the Rechna Doab are regulated through six major headworks. Four of these headworks, Marala, Khanki, Qadirabad, and Trimmu, are on the Chenab River, whereas the Balloki and Sidhnai headworks are on the Ravi River. These headworks enable diversions to the main and link canals servicing the irrigation areas. The Chenab and Ravi rivers meet about 64.4 km further downstream of the Trimmu headworks at the lower tip of the Rechna Doab area. Two main canals and five link canals take supplies from the Chenab River. The Upper Chenab Canal (UCC) and Lower Chenab Canal (LCC) are the main supply canals, taking water at the Marala and Khanki headworks, respectively. The five link canals—Marala-Ravi (MR), BRBD (Bambanwala-Ravi-Bedian-Depalpur), Qadirabad-Balloki (QB), Trimmu-Sidhnai (TS), and Haveli—mainly transfer water from the Chenab River to the Ravi River. Some of these link canals were constructed after the Indus Basin Treaty in the 1960s, which gave India exclusive rights to the Ravi River, greatly restricting flows into the Pakistani part of this river.

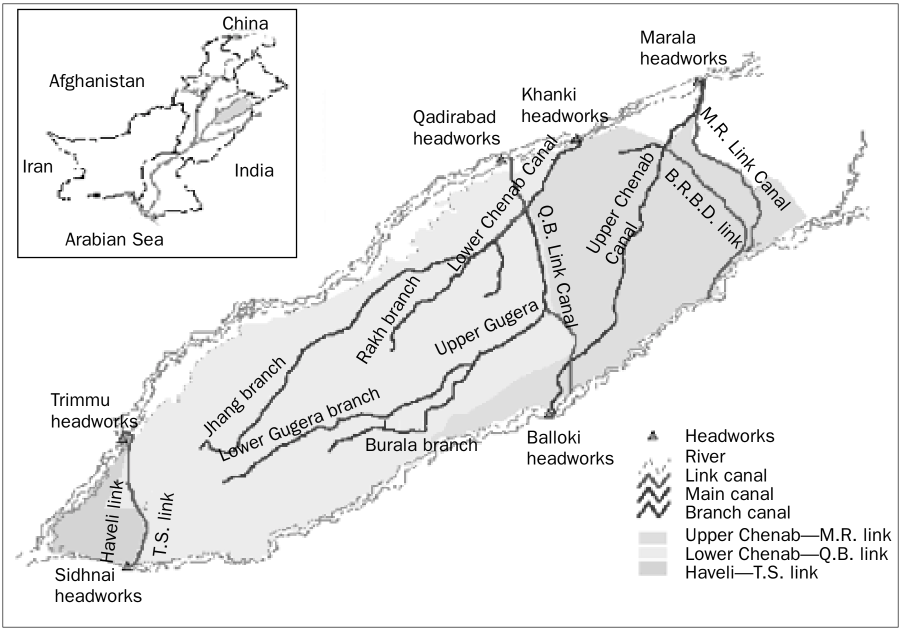

Fig. 1. The Rechna Doab irrigation system.

The study area falls in the rice-wheat and sugarcane-wheat agroclimatic zones of Punjab Province, with rice, cotton, and fodder crops dominating in the summer season (*kharif*) and wheat and fodder crops in the winter season (*rabi*). In some parts, sugarcane is also cultivated as an annual crop. At the time of construction, the irrigation network was designed to support low cropping intensities. However, the success of groundwater pumping from public and private tubewells to alleviate waterlogging and salinity problems in the late 1960s helped increase the cropping intensities to more than 150%. The groundwater storage underlying the Rechna Doab has served as a vital irrigation resource to support these increased irrigation intensities.

The Rechna Doab is a subtropical continental lowland often described as a semiarid region. The climate is characterized by large seasonal fluctuations in rainfall and temperature. The average annual precipitation varies from 290 mm in the south (Shorkot) to 1,046 mm in the north (Sialkot). The highest rainfall occurs during the monsoon period in July and August and accounts for about 60% of the annual rainfall. Because of the short time span of the monsoon, a large volume of rainfall is wasted and often causes floods. In the last three years, the monthly effective rainfall available for crop production has been very low throughout the Rechna Doab (Fig. 2; Soil Conservation Service 1972). However, no substantial reductions in crop yields have been reported in the region. This illustrates the increased dependence on groundwater resources to maintain the cropping patterns.

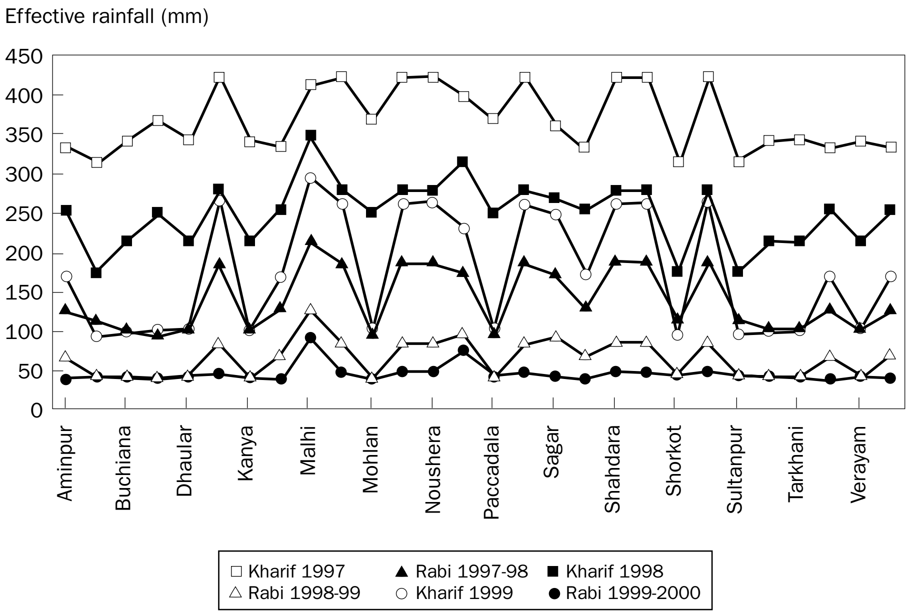

Fig. 2. Effective annual rainfall in Rechna Doab from 1997 to 2000.

Water balance analysis at the system scale

Realizing the importance of surface-water–groundwater interactions, the following two approaches were used to understand the role of groundwater in meeting crop demand on both hydrological and administrative area bases: (1) the top-down approach using a nodal network model and (2) the bottom-up approach using a surface-water–groundwater interaction model.

The top-down approach subdivides the study area into a system of channel reaches and demand nodes linking the channel reaches, and therefore follows the topography of the area. This approach recognizes data limitations, such as the lack of data on groundwater pumping rates, and therefore builds the desired complexity into the analysis only to answer specific questions. The bottom-up approach subdivides the area into several connected square grid cells in four layers, which can dynamically simulate the surface-water–groundwater interactions at varying depths and the quality of groundwater extractions represented by model layers. This approach requires better knowledge of the system and can integrate water and salt balances from individual cells up to the hydrological or administrative unit level.

Top-down approach

The study area was divided into three nodal networks, reflecting the direction of surface-water flow and connectivities of canals between the Chenab and Ravi rivers (Fig. 1): (1) Upper Chenab Canal and Marala Ravi Link Canal (UCC-MR) (Fig. 3),

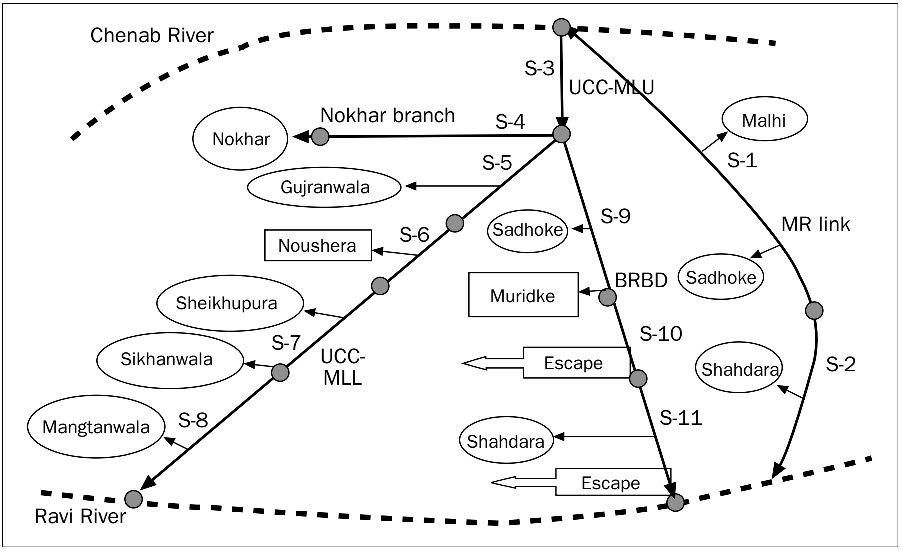

Fig. 3. Upper Chenab Canal and Marala Ravi Link Canal nodal network.

(2) Lower Chenab Canal and QB Link Canal (LCC-QB), and (3) Haveli and Trimmu-Sidhnai Link Canal (Haveli-TS).

A lumped monthly water balance was determined for each of the demand nodes using monthly canal supplies, irrigation system loss estimates, and net crop water requirement. This approach helped determine groundwater requirements by finding the difference between monthly water supplies and crop demand volumes in million m^3 using equations 1–3:

$$VGW = VNCWR - (VCH - VL) \quad (1)$$

$$VL = VMCL - VDL - VWCL - VFL \quad (2)$$

$$VNCWR = \Sigma(ETo \times Kc) - \text{effective rainfall} \quad (3)$$

where VCH = volume of water at head of network reach from canal flow data, VL = volume of all water losses, VGW = volume of groundwater required to meet crop water demand, VMCL = main canal seepage and evaporation losses, VDL = distributary seepage and evaporation losses, VWCL = water course seepage and evaporation losses, VFL = field seepage and evaporation losses, VNCWR = volume of net crop water requirement, ETo = potential crop water determined using Penman Monteith equation (FAO 1998), Kc = crop factors for individual crops grown in the demand area, and effective rainfall = rainfall available to crop after losses determined using Soil Conservation Service (1972).

To visualize the role of surface water in meeting crop demand, monthly canal water availability ratios (CWAR) were determined for each of the demand nodes:

$$\text{CWAR} = (\text{VCH} - \text{VL})/\text{VGW} \quad (4)$$

Examples of model results are presented for two demand nodes.

Example 1: Water balance for a node located in the upper part of the system. Figure 4 shows the CWAR and groundwater demand at the Nokhar demand node for 1997-2000 for the UCC-MR nodal network (Fig. 3). Although the Nokhar demand area is nonperennial (supplies water only in summer) and is located at the upper end of the irrigation system, results show that during both summer and winter the canal water supplies are not enough to meet crop demand and substantial groundwater pumping is necessary throughout the year.

Example 2: Water balance for a node located in the lower part of the system. Figure 5 shows the CWAR and groundwater demand at the Mangtanwala demand node for 1997-2000 located at the lower end of the UCC-MR nodal network. The water balance shows that the surface-water supplies are not enough to meet the crop water demand in both the winter and summer seasons. Similar results were obtained for the other demand areas in the Rechna Doab system, indicating a strong dependence of irrigated agriculture on groundwater pumping.

This analysis helped to establish the lumped spatial distribution of crop water demand, surface-water availability, system losses, and groundwater demand along

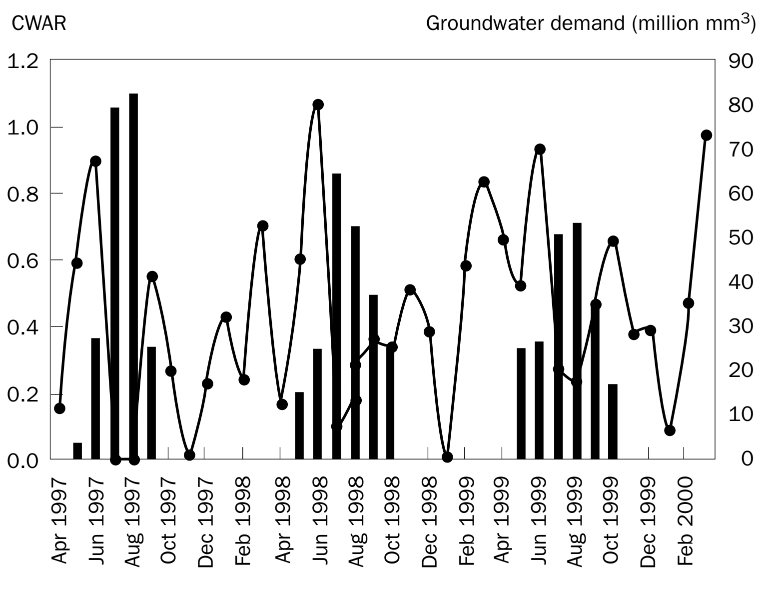

Fig. 4. Canal water availability ratio (CWAR; solid bars) and groundwater demand (line) in the upper end of the UCC-MR nodal network.

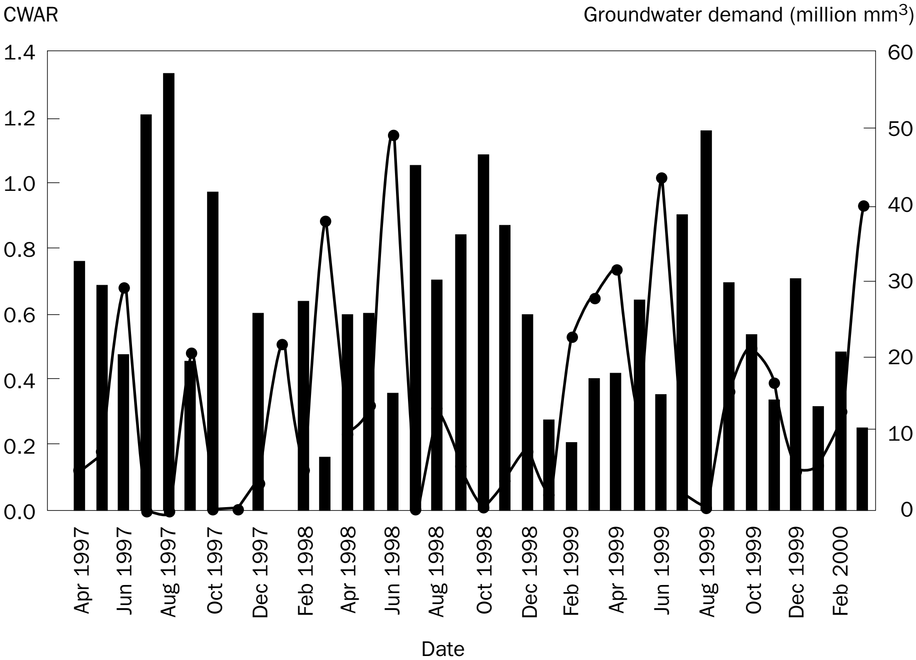

Fig. 5. Canal water availability ratio (CWAR; solid bars) and groundwater demand (line) in the lower end of the UCC-MR nodal network.

the irrigation supply system. This methodology provided a better understanding of surface-water and groundwater water-use efficiency on a nodal area basis but failed to quantify the contribution of losses from one part of the system to the groundwater gains in another part of the system.

Bottom-up approach

In bottom-up approaches, the biophysical processes are scaled up to the desired level of interest using biophysical parameters and process simulation at a more detailed level. In the case of Rechna Doab, the system was described with a surface-water–groundwater interaction model using MODFLOW and MT3D (Harbaugh and McDonald 1996, Zheng 1996, Khan 2001). The study area was divided into a matrix of $4 \times 106 \times 132$ cells of 2.5-km size in all directions, in which the four layers represented four aquifer layers. This arrangement required information on aquifer lithology, surface-water interactions, water quality, and recharge and discharge on a 2.5-km grid. This finer level of system description helped incorporate biophysical constraints to groundwater movement such as heterogeneity of alluvial aquifer properties and spatial variation in aquifer thickness.

Bennett et al (1967) provided a detailed hydrological description of the aquifer system in the Rechna Doab. The Rechna Doab aquifer system has a major discontinuity caused by a bedrock outcrop near Chiniot, which divides it into two semidependent basins (Fig. 6). The spatial variation in the thickness of Rechna Doab alluvium is shown in Figure 7. The alluvial sediments consist mainly of gray and grayish brown fine to medium sand, silty sand, silt, and clay (Khan 1978). The composite hydraulic conductivities of the alluvium range from 25 to 150 m d^{-1}. The shallow groundwater in the upper part of the Doab has low salinity (EC less than 1,000 $\mu S\ cm^{-1}$), whereas

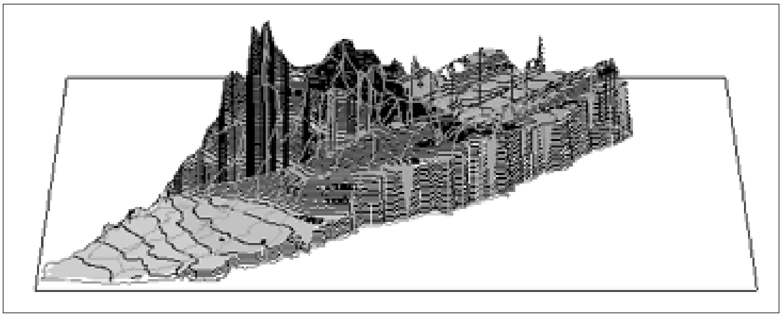

Fig. 6. Shape of the bedrock surface under the Rechna Doab. The numbers indicate the depth from mean sea level in m.

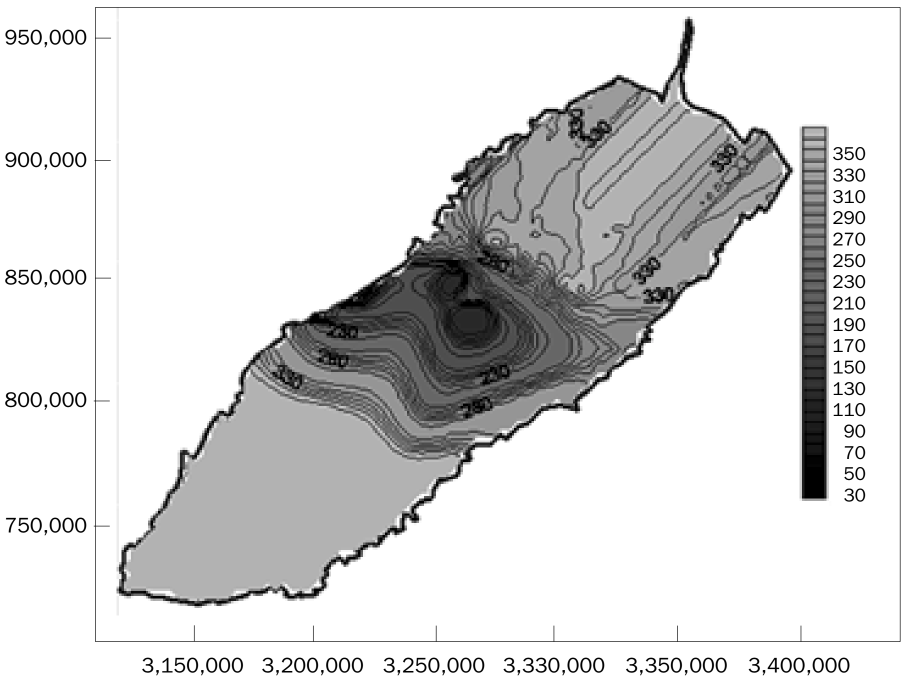

Fig. 7. Thickness of aquifers under the Rechna Doab (m). The horizontal and vertical axes are Universal Transverse Mercator (UTM) coordinates.

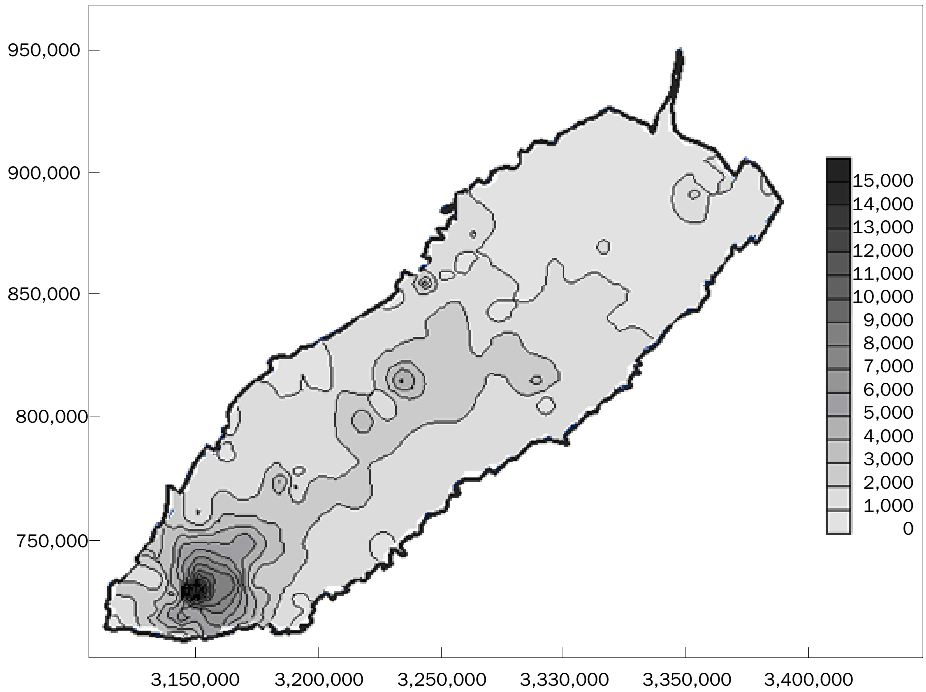

Fig. 8. Groundwater salinity under the Rechna Doab (µS cm^{-1}). The horizontal and vertical axes are Universal Transverse Mercator (UTM) coordinates.

the lower part of the Doab has higher groundwater salinity (EC ranging from 5,000 to 25,000 µS cm^{-1}) (Fig. 8).

Using the geometrical description of the surface-water network (rivers and channels), the surface-water–groundwater interaction parameters were defined in the model. The groundwater parameters such as hydraulic properties, recharge, water quality, evapotranspiration from the phreatic surface, and groundwater pumping were described on a cell-by-cell basis for each of the corresponding layers in the model. The evapotranspiration from the phreatic surface depends on soil type, water table depth, and land use. It consists of capillary upflow caused by plant roots and suction caused by evaporation at the soil surface. This model used water balance estimates from the nodal network approach as sanity checks for the water budget outputs. The combined description of surface-water and groundwater systems at a finer scale helped to dynamically simulate the system response to changing surface-water availability and rainfall scenarios on a seasonal basis.

The model was calibrated for a seven-year period from June 1993 to June 2000 at 190 piezometric locations throughout the Rechna Doab. Forecasts were made for October 2000 to June 2003 using weather data of 2000 and an increased groundwater pumping regime (stimulated by recent dry-weather conditions). Figure 9 shows simulated and observed piezometric levels at a representative location in the middle of the Doab for the calibration and the forecast period. The cyclic nature of the simulated and observed hydrographs in the initial five years shows that groundwater in the aquifer is stored during the summer (because of excess recharge from the rivers, channel network, and field losses) and is used during the winter. In the last two years of the historic simulation period, the water tables decline. This declining groundwater trend continues in the forecast simulation period because of the increased groundwater pumping and the lower surface-water supplies (caused by below-average rainfall). This situation requires careful groundwater management in the Doab as overexploitation of groundwater can make pumping operations expensive and can mobilize saline groundwater.

Figures 10 and 11 show the groundwater balance scaled up to the Doab level for the winter of 1996 and the summer of 1997, respectively. This water balance quantifies the relative magnitudes of groundwater pumping (WELLS), evapotranspiration from the water table (ET), groundwater recharge (RECHARGE), river and channel seepage (LEAKAGE), and change in groundwater storage (STORAGE). The positive storage terms in the winter indicate that groundwater demand is partly met from aquifer storage, whereas the negative storage terms in the summer indicate that excess groundwater recharge is stored in the aquifer.

Figure 12 shows predicted groundwater levels in June 2003. Because of a dependence on groundwater, the lower parts of the Doab develop water-table depres-

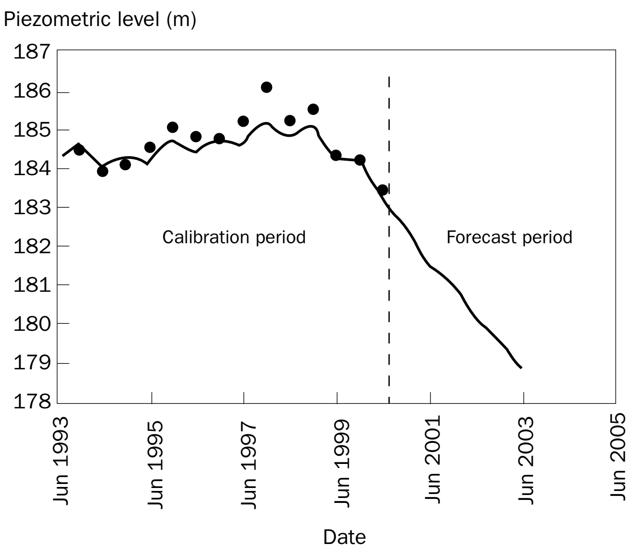

Fig. 9. Observed (●) and simulated groundwater levels (line) at piezometer L-28/11 in the middle of the Rechna Doab.

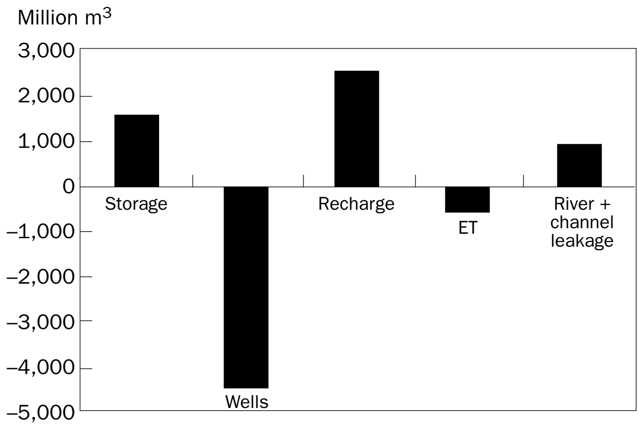

Fig. 10. Winter 1996 groundwater balance for Rechna Doab.

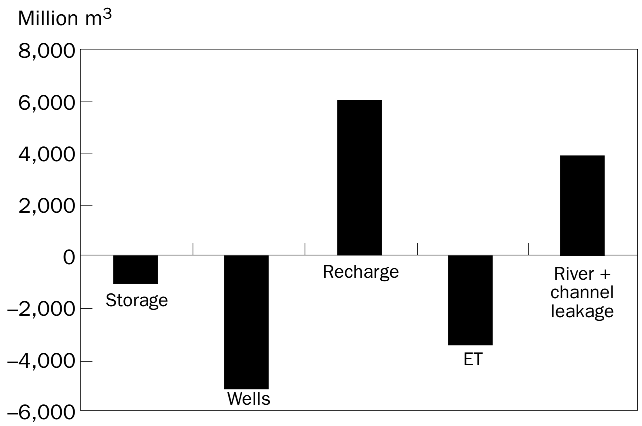

Fig. 11. Summer 1997 groundwater balance for Rechna Doab.

sions with depths greater than 15 m, which can make groundwater pumping uneconomical for farmers because of the many-fold increase in capital and operating costs. These water-table depressions can cause mobilization of saline groundwater from adjacent regions and from deeper groundwater. An example of degrading water quality with increased groundwater pumping under continued dry climatic conditions is given in Figure 13 for the lower part of the Doab (Haveli Division L-03/3).

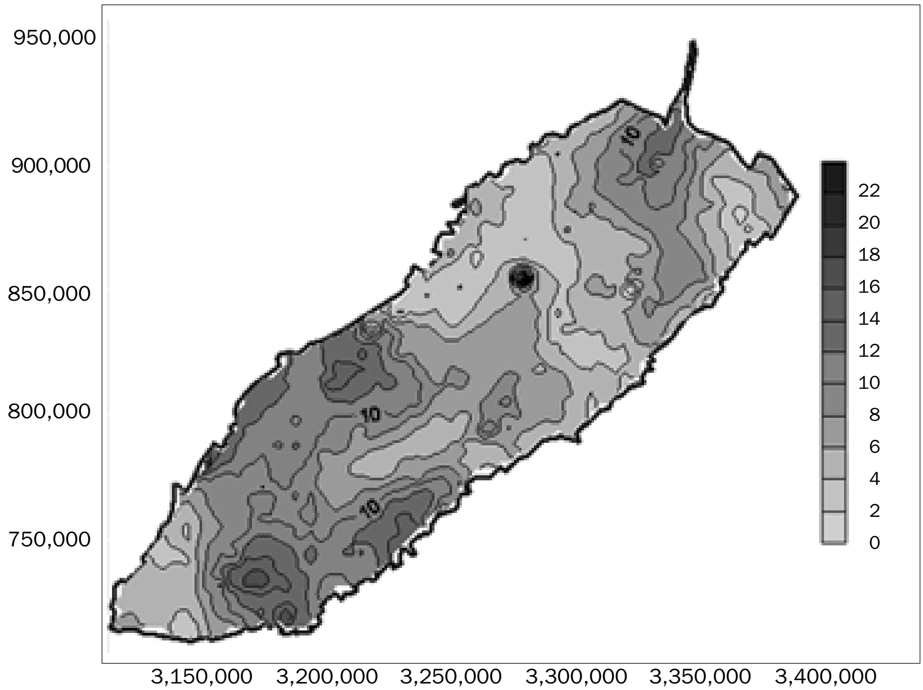

Fig. 12. Predicted depth of the water table below the soil surface (m) for June 2003. The horizontal and vertical axes are Universal Transverse Mercator (UTM) coordinates.

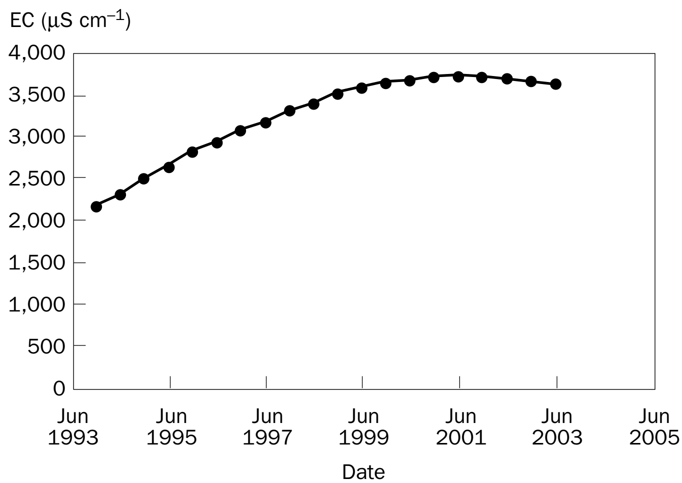

Fig. 13. Predicted salinity in the shallow aquifer under the Haveli Division L-03/3.

Conclusions

This paper demonstrated two approaches for quantifying surface-water and groundwater balances in groundwater-dominant systems. The top-down approach is useful in situations where data on the distributed features of the system are scarce, while the bottom-up approach is more suitable for data-rich environments. The top-down approach can help get a handle on relative quantities of different hydrological components distributed along the supply system. This type of methodology is recommended for rationalization of resource allocations along supply networks. However, this approach fails to quantify how losses from one demand node can become gains to other demand nodes in the system and how water-quality transformations take place in this process. The bottom-up approach offers integration of information from a lower level to any desired level of detail but requires huge data sets and intellectual investments. Its distributed nature can help represent system discontinuities and heterogeneities. This approach can easily be coupled with methods to account for water quality to add the vital water-quality dimension to the water-balance debate. The distributed nature of the bottom-up approach facilitates the lumping of water balances at the desired hydrological or administrative units. The ability to link the groundwater balance with water-quality dynamics offers a tremendous tool for policymakers for defining the rational productive use of surface water and groundwater without compromising environmental conditions.

The water-balance studies for Rechna Doab have shown that, in the summer, crop water demand is partly met from mining of aquifer storage, whereas, in the winter, excess groundwater recharge is stored in the aquifer. The long-term sustainability of groundwater is threatened in lower parts of the Doab because of the development of water-table depressions with depths greater than 15 m, which can make groundwater pumping uneconomical for farmers. These water-table depressions cause mobilization of saline groundwater from adjacent regions and from deeper groundwater.

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Options for regional water savings and reallocation

W.N.M. van der Krogt and R.J. Verhaeghe

Water savings at the micro level, constituting a reduction in evaporation and percolation losses and/or an improved matching of water supply and demand, are only effective if the savings at one place and time can be reallocated at a different time and/or different place to a different user. The regional configuration of the water resources system and the way it is managed strongly determine the possibilities for reallocation and thus the overall effectiveness of water savings. An overview is presented of different water supply systems and the role of operational management in the potential to save and effectively reallocate water. The concepts are further illustrated with simulations for the complex Citarum River basin (Indonesia). The tests for this basin demonstrate that savings in irrigation water supply through demand management and operational management are very promising for systems with a large irrigation component. Such measures can strongly contribute to an effective use of scarce water resources.

Water savings in rice production at the field level should be translated into water availability for other purposes at a larger or regional scale. The alternative use of the saved water determines its value. Effectuation of such water savings forms part of the overall water management for the river basin. The problem of upscaling of systems at the field level to identify benefits at a regional scale and the role of the configuration of the regional system in this are the main topics of this paper.

Different types of water supply systems have different potentials for effectuating water savings and may require specific operational management. Below, we first review a set of typical water supply systems and present an inventory of the factors influencing effectiveness. Then we present a case study of a complex basin (Citarum, Indonesia) containing most of the presented factors. Linking the field level with the total water system requires appropriate analytical tools to describe the field process as well as the total system. An application of such a tool is presented in the case study by giving a quantitative estimation of the potential for water savings in basins with scarce water resources.

Demand and supply systems

Essential elements in the analysis of water supply systems are the following (Suyanto and Verhaeghe 1998, van der Krogt and Verhaeghe 2001, Verhaeghe and Sonneveld 1993):

- the different sources of water supply and their characteristics,
- the different water demands with their characteristics,
- the configuration for water allocation, and
- operational management.

Types of supply and demand

Supply. For surface water, a differentiation can be made between uncontrolled (free river flow) and controlled surface water (releases from reservoir). The type of climate and the resulting variation of river flow strongly determine the value of both types of surface-water sources and in particular uncontrolled runoff. Groundwater constitutes supply from storage; if it can be extracted from an aquifer located underneath the demand area, then significant savings can be realized (in comparison with surface water) in the distribution of the water (reduced transportation costs, reduced water losses, reliable supply). On the other hand, the amount that can be extracted at a particular point is relatively limited and expensive; hence, groundwater is not suited for large quantities. In many cases, groundwater is overused, resulting in a nonsustainable situation with mining of the aquifer and declining groundwater levels.

Demand. A main differentiation can be made between a constant and time-variable demand. The domestic, municipal, and industrial (DMI) water requirement is usually a steady demand, whereas irrigation has a strongly varying demand according to the cropping pattern and climate. Hydropower generation aims at a steady and high power supply. Depending on the downstream flow path, the water used for hydropower can be considered consumptive or nonconsumptive.

If there is a strong variation in the supply and demand, a careful timing of demand activities is required to optimize water use. Similarly, if water savings can be realized at the field level, an appropriate timing is needed to effectuate these savings. For irrigation, timing of the irrigation activities concerns the use of rainfall and the supply from other sources (e.g., river flow) through the canal system. Figure 1 illustrates such timing with the planning of two irrigated crops with respect to the rainfall pattern. If the objective is to realize two irrigated crops, matching will result in a first crop established before the onset of the rains and a second crop at the end of the rainfall period. Especially, the start and the end of the season require an irrigation water supply that should be available from a river or reservoir. The matching of the cropping schedule with the rainfall pattern results in a one-half month shift ahead of the current cropping schedule (Fig. 1). This shift affects both the peak requirement and the irrigation water volume. Implementation of water savings at the field level will alter the demand pattern and requires an adjustment of the timing of supply and demand.

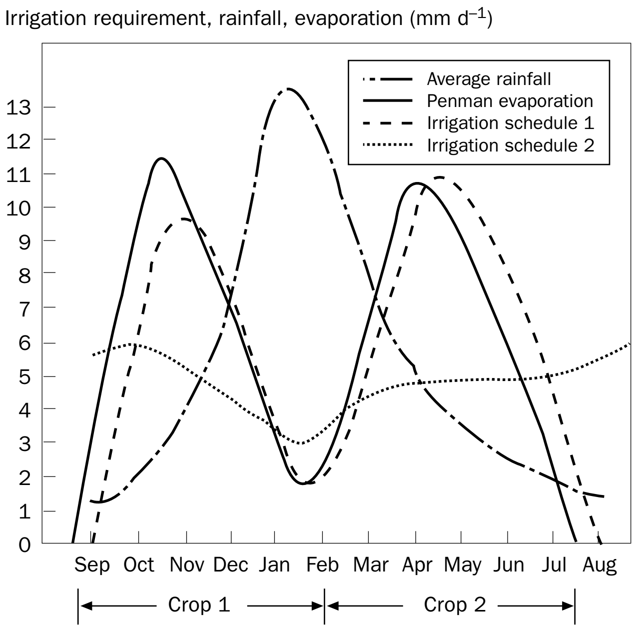

Fig. 1. Matching the cropping schedule and irrigation water supply with the rainfall pattern to optimize water use.

Typical supply-demand systems

The most simple system is the diversion of water from an uncontrolled river. If there is one irrigation scheme only, reallocation of water savings is limited to an internal reallocation for an expanded irrigation area and/or increased water supply to existing crops. If there are several irrigation schemes (Fig. 2), savings can be used downstream. A basin-wide management is necessary to coordinate water use among irrigation schemes.

The introduction of a reservoir (Fig. 3) allows the carryover of water from one time period to another, and thus strongly increases the potential to effectively reallocate water. An adequate basin-wide management is necessary to match reservoir releases to the demands from different irrigation schemes.

A frequently encountered situation is a storage-controlled source in combination with an uncontrolled source serving the same demand(s) (Fig. 4). Operational management plays a key role in this case: in view of the possibilities to store water in the reservoir, the operational management strategy will be oriented toward using the uncontrolled source as much as possible and supplementation from the reservoir where needed.

For most water users, part of the supplied water is used consumptively and the rest is returned to the river basin as return flow. The positioning of the different demands and the path of the return flow determine whether this return flow can be used (again) by another user. For example, for a set of water users located in series in a downstream direction and with return flow returning to the river before the intake of

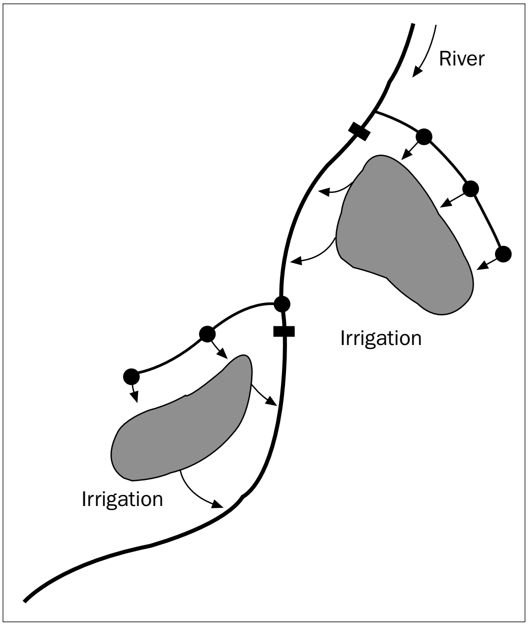

Fig. 2. Uncontrolled source of irrigation.

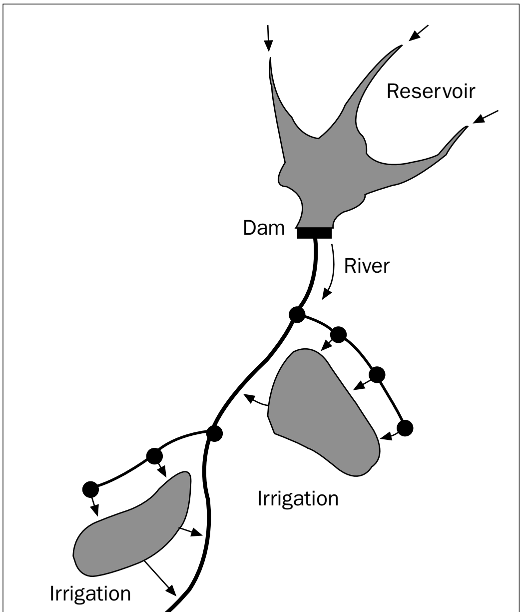

Fig. 3. Controlled source (storage) of irrigation.

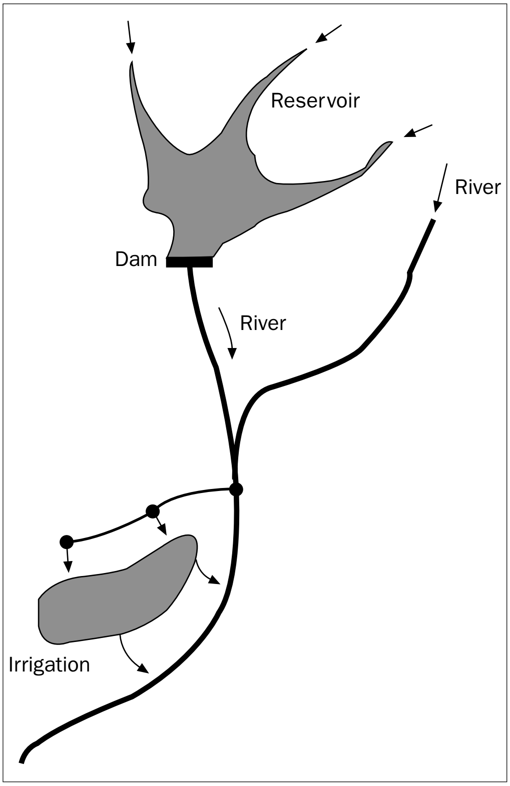

Fig. 4. Controlled and uncontrolled sources of irrigation serving common users.

the next user, an optimal reuse can be made of the return flow. For a set of parallel demands located on a coastal floodplain, for example, return flow will be of little use.

A multipurpose water supply system with different users complicates water allocation and increases the requirements for an adequate operational management (Fig. 5). The possibilities to reallocate water can be enhanced if the demand and its timing can be matched with each other. There is also the possibility of a joint risk management. For example, if public water supply and irrigation are involved, irrigation (which has a lower priority) can be used as a buffer during shortage periods. Farmers can be compensated for their incurred losses.

Operational management

Operational management is an essential element for all water systems to realize an optimum water use for a given infrastructure. A main distinction can be made between supply- and demand-oriented management. Options in demand management are

- Reductions in demand because of reduced losses in piped water distribution or technological changes in irrigation practices, improvement of irrigation

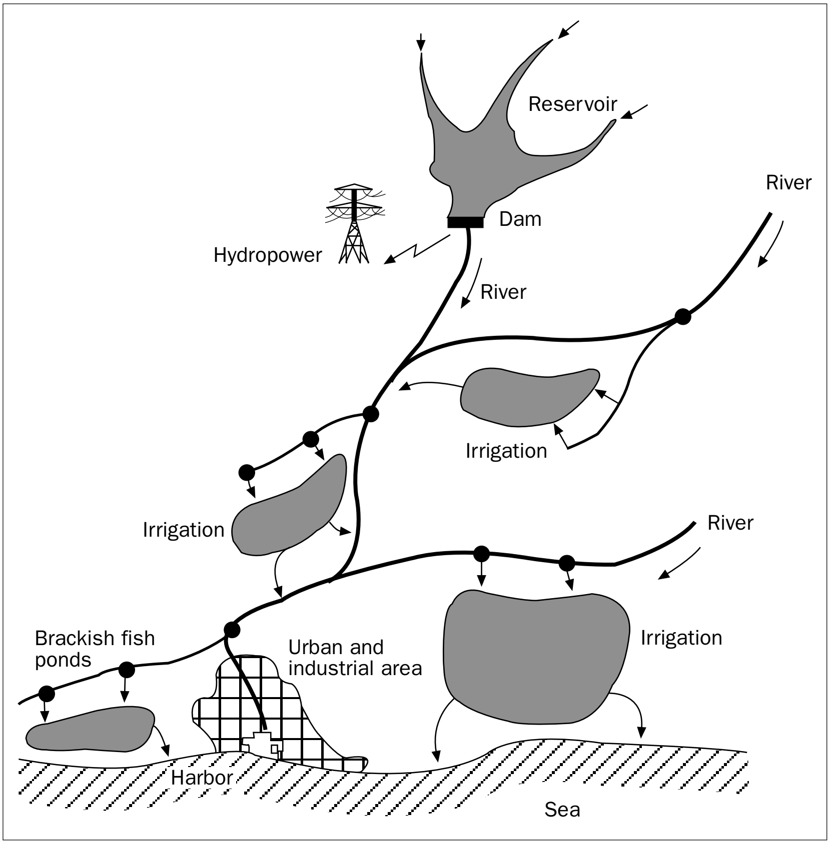

Fig. 5. Controlled and uncontrolled sources of irrigation serving different users.

scheme management, and changes in agricultural activity (e.g., different cropping pattern). Those changes may result from research or improved financing or may be induced by scarce water resources or societal changes.

- Feedback from the field to adapt the water supply to the real-time conditions in the field.
- Allocation management during a shortage: hedging on the supply to particular demands, taking into account the priority among different users, the effects of reductions for different users, and the gravity of the shortage situation.

Options in supply management are

- Management of stored (reservoir) water over time so that maximum benefits are realized for the different users.
- Management of reservoir and uncontrolled sources, including the maximization of water use from the uncontrolled sources.

- Prediction of flow in the uncontrolled river and/or inflow to reservoir(s) can improve allocation substantially by allowing a better matching of supply and demand.

Case study: the Citarum basin

The Citarum basin in Java, Indonesia (Fig. 6), is a complex basin containing most of the features of water systems presented above: storage and uncontrolled sources, multipurposeness, and potential for all forms of operational management. Demand management and advanced operational management have the potential to drastically improve the effective use of available water resources in this basin. There are three large reservoirs along the Citarum River: Saguling, Cirata, and Jatiluhur (see Table 1 for details). Hydropower is generated at each of these reservoirs. The main water user is an irrigation scheme (240,000 ha) in the downstream part of the basin. Municipal

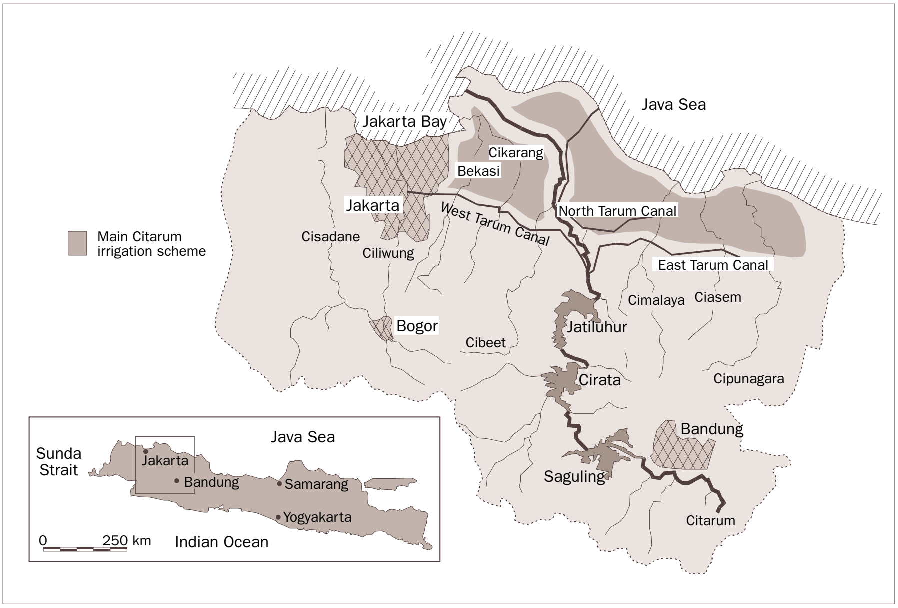

Fig. 6. The Citarum River basin.

Table 1. Characteristics of the three reservoirs in the Citarum basin.

Reservoir	Total storage (million m^3)	Power capacity (million W)	Catchment area (km^2)	Av annual inflow (million $m^3\ y^{-1}$)
Jatiluhur	2,970	175	4,655	5,613
Cirata	1,970	518	4,179	4,888
Saguling	880	715	2,361	2,491

and industrial water supply is provided to the Jakarta region. Water is distributed through three main canals: the East, West, and North Tarum canals (Fig. 6). These canals intercept water from local rivers and receive water from the Jatiluhur reservoir. The contribution of water from the local uncontrolled rivers is substantial and constitutes about 60% of the total water supply during the wet season and 40% during the dry season. The tropical climate has a distinct wet and dry season, with on average 70% of rainfall falling from December to April.

The domestic, municipal, and industrial (DMI) water demand in the region around Jakarta is projected to increase strongly in the future. The Citarum basin has the potential to provide an increased supply, but this requires careful planning of water allocation to the different water users. Supplying the extra DMI demand will stretch available resources to the limit and additional measures will be necessary to accommodate the increasing demand. The firm (water) flow from all sources (with present operational management) is practically fully used and possibilities to create extra storage are limited in this region with dense settlement. Improvement in the use of existing facilities through advanced operational management is an attractive alternative.

The water balance of the basin has been analyzed with the RIBASIM (RIver BAsin SImulation Model) simulation package (Delft Hydraulics 2000). Figure 7 gives the schematization of the basin with a network of nodes and links. The nodes represent reservoirs, dams, weirs, pumps, hydropower stations, water users, inflows, man-made and natural bifurcations, intake structures, natural lakes, etc. The links represent the transportation of water between the different nodes. Such a network represents all of the basin's features, which are significant for its water balance, and can

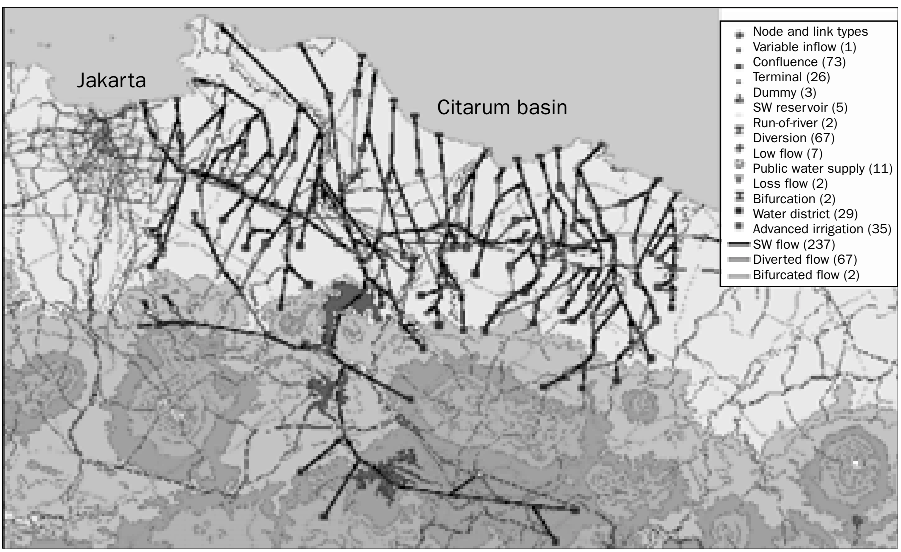

Fig. 7. Schematization of the Citarum River basin.

provide the required level of detail to represent the features of the demands, basin configuration, and hydrology. This network and the required data for each network element can interactively be entered through the user interface, which uses a map of the river basin (different map layers) as reference background.

The DMI demand for the Jakarta region is expected to increase to a total of 77 $m^3 s^{-1}$ (presently 25 $m^3 s^{-1}$) in the next 25 years. The potential water supply for the Citarum system under current conditions (configuration and management) is 125 and 50 $m^3 s^{-1}$ for irrigation and DMI supply, respectively.

Based on analyses of the water balance of the basin (DGWRD 1994, 1997), the increasing requirements can be met with the following measures:

- On-demand irrigation (firm flow: +5 $m^3 s^{-1}$): more accurate estimation (real-time) of the irrigation demand for the coming time period, allowing irrigation system managers to match water allocation more precisely with the actual requirement.
- Drought management (firm flow: +10 $m^3 s^{-1}$): in case of an extreme drought situation or in anticipation of such a drought, part of the irrigation scheme may be disconnected to save water for the first-priority water user, DMI; the farmers are then reimbursed for their losses.
- Flow prediction (firm flow: +10 $m^3 s^{-1}$): the on-line prediction of flows of uncontrolled rivers, tapped by the main Tarum canals, can increase their contribution to the firm flow with about 10 $m^3 s^{-1}$.
- Raising the level of the Cirata reservoir (firm flow: +15 $m^3 s^{-1}$): the middle reservoir, Cirata, has been built with the intention that it could be heightened in the future; this will substantially increase total storage in the reservoir cascade and increase the firm flow from the system.

Most of the needed extra supply can thus be provided through an improved operation management of the existing system. A further option to adjust the water balance involves demand management that focuses on changing the cropping pattern to include fewer water-consuming crops. Such an option is in line with a change toward vegetable and fruit crops for which demand is increasing in the growing Jakarta urban region. To illustrate the sensitivity for such a change in cropping pattern, a RIBASIM simulation was carried out for a new cropping pattern in which 10% of the current area cultivated with rice was exchanged for vegetable growing. Figure 8 illustrates the unit water requirements for the old and new cropping pattern. The simulations indicated an 8 $m^3 s^{-1}$ increase in the DMI water supply potential. Such an amount is equivalent to the water supply of a new reservoir (Tanjung), which could be built to the east of Jakarta to provide extra water. The investment cost for Tanjung has been estimated at US$125 million. This cost illustrates the value of demand management and operational management measures. Other measures that influence water use in irrigation can be expected to have similar effects on the water balance.

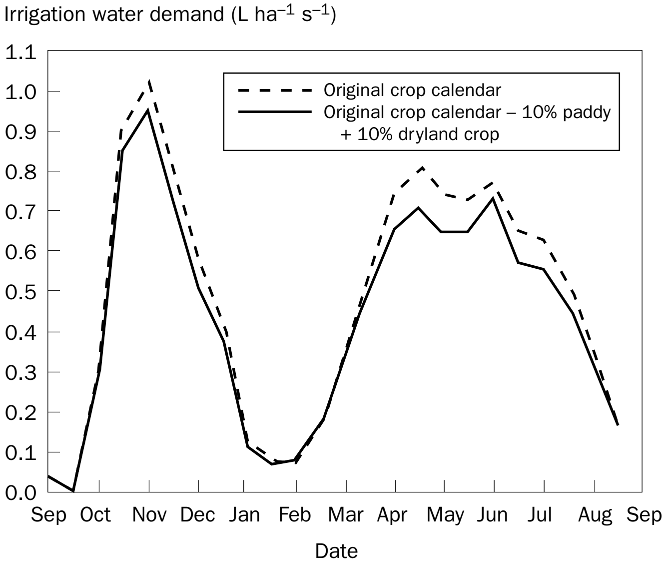

Fig. 8. Unit water requirements for the old and new cropping pattern.

Observations and conclusions

The review of different water systems and the simulations for the Citarum basin illustrate that an appropriate planning and operational management at the basin level is required to effectuate savings at the field level and to make the necessary allocation decisions involving timing and storage management and distribution among users.

The computations for the Citarum basin and the comparison of effects of different water-management measures confirm that changes in irrigation water demand through improved irrigation technology, an adapted cropping pattern, or advanced operational management can be promising alternatives to resolve scarce water resource situations. This is particularly so for systems in which irrigated agriculture is the largest water consumer, which is the case for most river basins. The potential for advanced operational management to increase the firm flow from an existing water supply system can be substantial. In a situation with a tight water supply and limited available options for improvement, such an increase may represent a large alternative value.

Incorporation of the options for water savings and evaluation of the overall system effects require an appropriate simulation tool with sufficient functionality to represent the relevant features at both the micro level and larger systems level. RIBASIM has much of the functionality to simulate such a system.

It remains a challenge to translate potential improvements, such as suggested in this paper, into actual improved water management. There are substantial organizational requirements. Establishing an adequate database and monitoring capability as well as the analytical means to determine the effects of alternative measures is an essential part of implementation.

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The effects of pumping on water use and profitability in dry-season rice: a case study in UPRIIS, Philippines

P.F. Moya, D. Dawe, and S. Valencia

Farmers in many parts of Asia are increasingly using pumps to irrigate their rice crops. This has occurred because pumps have become less expensive and because of an increased scarcity of gravity-flow surface water. One such system is the Upper Pampanga River Integrated Irrigation System in Nueva Ecija, Philippines, where this study was conducted. In spite of the high cost of pumping water, pump users in our survey still received a substantial amount of farm profits from rice production, although less than those with good access to a surface gravity system.

There are no significant differences in yields or input use between farms irrigated by pumps and the surface gravity system, with the exception of water use. Farms that rely on pumping irrigate fewer times and have a lower degree of flooding. Land rents are higher for farms with good access to gravity-flow water compared with farms that rely heavily on pumping. It is important to note that the findings of this study are applicable only to this specific site, especially since rice prices are substantially higher in the Philippines than in neighboring countries. Additional studies on the economic and water management effects of pumping in different parts of Asia would provide useful information.

A majority of the irrigation systems in the Philippines have an adequate water supply to irrigate their design area during the wet season (WS). However, during the dry season (DS), water scarcity exists so that only part of the service area can be supplied with surface irrigation water (Maglinao et al 1993). In such areas, the conjunctive use of surface water and groundwater has become common in the tail-end sections where the supply of surface water is inadequate to sustain a dry-season crop. Farmers may pump water from underground, creeks, rivers, or drainage canals to supplement scarce or delayed supplies of water from surface irrigation systems. In some cases, farms rely solely on pumping for irrigation even though they are within the service area of the gravity system. This is common not only in the Philippines but also in Indonesia, where pumping of groundwater was done to supplement the water supply during the DS (Bhuiyan 1993, Undan et al 1992).

One such system where the use of small pumps to augment gravity-irrigation water supplies during the dry season is common is the Upper Pampanga River Integrated Irrigation System (UPRIIS) in Nueva Ecija, Philippines. There are four districts in UPRIIS, which has a total design service area of about 102,000 hectares. This study was conducted in District I, which has a service area of about 28,000 ha. According to data provided by the National Irrigation Administration (NIA), 2,176 farmers use water pumps to augment their irrigation water supplies in District I alone, covering more than 4,000 ha. This is about 14% of the service area of District I. Nearly all (94%) of these farmers pump groundwater, with a small minority pumping surface water from canals or rivers.

The objectives of this study were to (1) compare the on-farm water management practices of different types of farmers within UPRIIS (some who irrigate their field through a surface gravity system, some who use only a pumping system, and some who use gravity and pumped water conjunctively); (2) compare profitability, yield, and input use among these groups of farmers; and (3) determine the factors affecting the variability in the amount of water used by different farmers.

Data collection and sample description

To attain the above objectives, detailed data were collected through farmer interviews immediately after the cropping season of DS 2000 on yield, input use (including labor), prices of inputs and outputs, and water management practices. A total of 60 farmers were selected within the service area of Lateral F of District I of UPRIIS (Fig. 1), with 20 farmers being selected from each of the upper, middle, and lower reaches of the lateral. In the upper reaches of the lateral, many of the farms are located at a higher elevation than the surface canals, so water will not flow to their fields unless lifted by a pump. In the middle reaches of the lateral, farmers can irrigate without resort to pumps and are able to rely entirely on gravity flow from the surface irrigation system. In the lower reaches of the lateral, many farmers pump groundwater with small, individually owned pumps. Some of these farmers rely exclusively on groundwater, but most use groundwater and gravity-flow surface water conjunctively (Table 1).

The sample farmers have more or less similar characteristics in age, schooling, and family size. The most common rice varieties planted in the area are IR64 and other modern varieties released by the Philippine Seed Board (PSBRc varieties). Nonrice crops are planted in some fields during the dry season; the most popular crops are onions, maize, eggplant, string beans, and bittergourd.

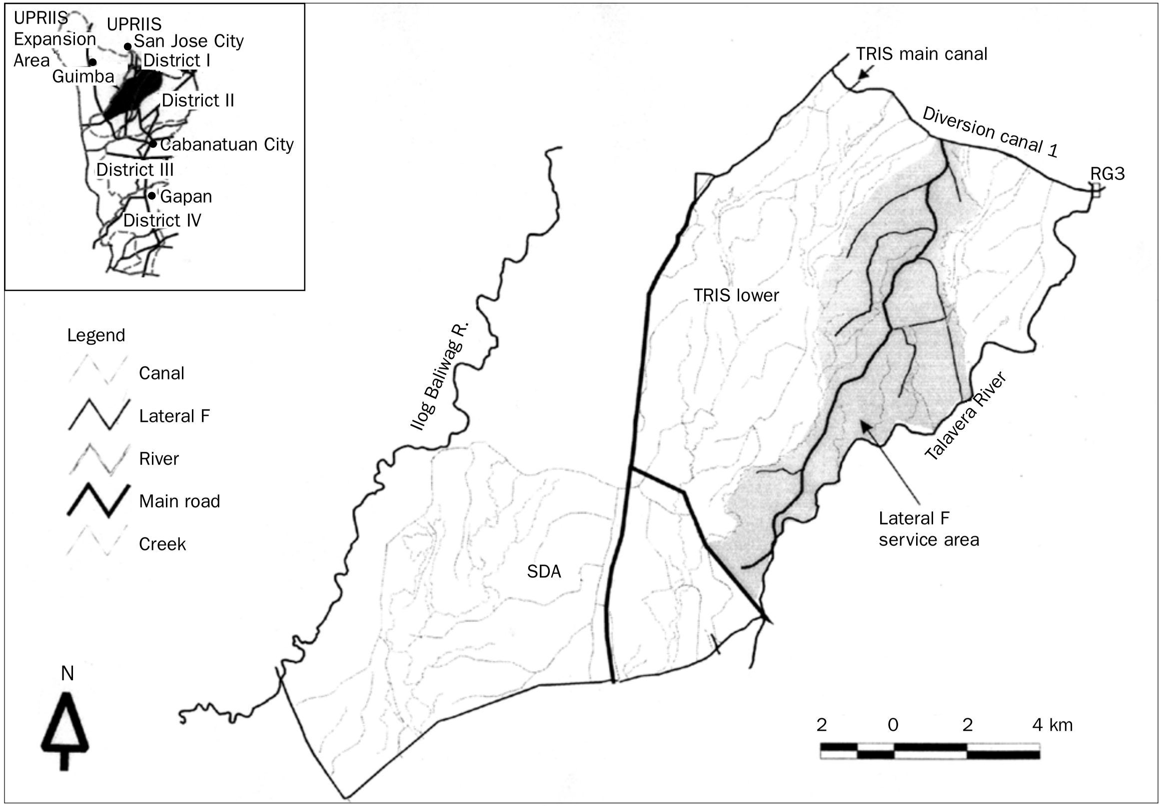

Fig. 1. Map of District 1 (partial) of UPRIIS, showing lateral F service area where our interviews were conducted.

Table 1. Distribution of sample farms by water source and water delivery system, UPRIIS, Nueva Ecija, dry season 2000.

Location	Number of samples	Water source		Water delivery system				Dominant water delivery system[b]	
		Surface water	Ground-water	Both[a]	Gravity	Pump	Combination	Gravity system	Pump system
Upstream	20	13	6	1	0	19	1	1	19
Midstream	20	20	0	0	20	0	0	20	0
Downstream	20	0	7	13	0	7	13	11	9
Total samples	60	33	13	14	20	26	14	32	28

[a]Farmers draw water from both surface and underground. [b]If farmers use the surface gravity system for 50% or more of their irrigation event activities, they are classified under the gravity-system category.

Water management at the farm level

Water sources and systems of water delivery

Among the 60 sample farmers, 33 (55%) used exclusively surface water (irrigation canals, drainage canals, creeks, or rivers), 13 (22%) used exclusively groundwater, and 14 (23%) used both sources. In terms of delivery systems, 20 used exclusively gravity-flow surface water, 26 exclusively pumped (either from groundwater or surface water), and 14 used gravity flow and pumped water conjunctively.

There are many reasons why farmers use pumped water in conjunction with gravity-flow water. Many of the reasons revolve around harvesting the DS crop early, which allows for easier drying of the crop before the onset of the rainy season and also allows for the additional planting and harvest of a short-duration cash crop (e.g., sweet potato, mustard) before the planting of a WS rice crop. Several farmers also noted that they received a higher price for their crop if the DS crop was planted earlier. In addition, the use of a pump allows farmers to synchronize crop establishment date with other farmers in the area to minimize the attack of insects, pests, and diseases. Pumps also allow them to avoid various risks if water deliveries from the gravity system are inadequate or delayed.

Marginal cost of pumping

In the Philippines, farmers who use only gravity-flow surface water have a very low marginal cost of using water. They must pay a water fee to the NIA, but this fee is independent of the quantity of water consumed. Farmers who pump have a higher marginal cost of water use because they must pay for both fuel and depreciation of the pump. Thus, farmers who resort to pumping will probably use less water than those who rely on gravity flow. Before testing this hypothesis with our data, we first calculate the marginal costs of an additional irrigation event for the different types of farmers.

The marginal cost of an additional irrigation event is composed of three costs: labor costs (because of the time spent in carrying out the irrigation), fuel costs, and depreciation of the pump. When gravity-flow water is used, the only relevant component is the labor cost associated with opening and closing the inlets to the field. One must also consider the time involved in going from the house to the field and back, as well as any time spent waiting in the field. It is not necessarily clear whether to attribute a cost to this time. If the farmer was going to the field for other purposes anyway, and just happens to irrigate while these other tasks are carried out, the marginal labor cost of an irrigation event is very close to zero. On the other hand, if the main purpose of the trip to the field was to irrigate, the costs of that time should be counted as a cost of irrigation. In our sample, many farmers need to stay in the field for several hours to make sure that, once they open the inlets, other farmers do not close them in an effort to divert water. In such cases, there is clearly an opportunity cost to their time: they would rather be doing something else. On the other hand, some farmers go out to the field regularly, even if they are not carrying out any farm activities. These farmers are often older, and for them farming appears to be something of a hobby. In these cases, there is no opportunity cost to their time, and the marginal labor cost of an additional irrigation event is zero. Based on the results of our survey, farmers spend an average of 8.6 hours in the field per irrigation event. If we attribute an opportunity cost to this labor at the prevailing farm wages in this part of the Philippines, the marginal labor cost of an irrigation event is about US$2.47.

The marginal cost of fuel per irrigation event is more straightforward than labor costs because all fuel must be purchased. We calculate this cost as $1.47 per irrigation event, based on our survey data.

Depreciation of the pump must also be accounted for in understanding the marginal cost of an irrigation event since the pump will wear out more quickly if it is used frequently. Some farmers in the area rent out their pumps on an hourly basis, and they charge on average $0.51 per hour to compensate for wear and tear on the pump (the renter must pay for all fuel costs). Multiplying this hourly rate by the average number of hours per irrigation event gives a depreciation allowance of $4.37 per irrigation event.

In estimating the marginal cost of an irrigation event for a particular farmer, it is important to distinguish between pump renters and pump owners. This distinction is important because most pump rental is done on a seasonal basis and is independent of the amount of water pumped or the number of times the pump is used. A typical rental rate is 10% of the harvest, with the renter paying the cost of diesel fuel. Since in these cases the pump rental will not increase if there are one or two additional irrigations, pump renters do not face this marginal depreciation cost in their decision to irrigate. Pump owners, however, must consider these depreciation costs.

Taking all these factors into account, we calculate the marginal cost of pumping as follows. First, for farmers with access to gravity-flow water, the marginal cost of an irrigation event is just the labor cost, or $2.47 per event. For pump renters, the marginal cost is the sum of labor costs and fuel costs, or $3.94 (= $2.47 + $1.47). For pump owners, the marginal cost is the sum of labor costs, fuel costs, and depreciation, or $8.33. These calculations suggest that the marginal cost of an irrigation is determined more by depreciation than by fuel costs. It also suggests that pump owners might irrigate less frequently than pump renters.

Determinants of water use across farms

As noted earlier, there are three main types of water-delivery systems in our sample: gravity flow pumps, or conjunctive use of both systems. However, the third group (14 farmers) turns out to be composed of two main groups: those who use primarily gravity flow and those who use primarily pumps. Only three farmers have one-third or more of irrigation events from both gravity flow and pumps. Thus, to compare water use among farmers in a more simple fashion, we group all farmers into one of two groups based on their dominant water-delivery system: gravity or pump. We drop the three abovementioned farmers from further analysis, although their inclusion does not affect the conclusions substantially.

To measure water use, we asked farmers the depth of the water layer in the field at the end of each irrigation event. We then summed these depths for all irrigation events to calculate a cumulative depth of water applied. Note that this is not a measurement of water flow into the field. For example, for a given irrigation event, a farmer with a porous soil may have the same depth of water in the field at the end of the event as a farmer with a clay soil, even though the farmer with the porous soil experienced more percolation losses during the event and thus consumed more water. Cumulative water depth, however, is a measurement of the degree to which farmers keep their fields flooded.

The average cumulative depth of water applied by pump users, from the initiation of land preparation to harvest, is 1,262 mm. Gravity-system users applied a slightly higher amount, 1,466 mm, a difference of 14% (Table 2). Because of the high degree of variability across users, this difference is not statistically significant (P value = 0.33). In terms of number of irrigations, pump users irrigated an average of 16.3 times compared with 20.8 times for farmers using primarily gravity flow. This difference is statistically significant at the 5% level.

We also compared the degree of flooding according to different crop establishment methods. Slightly more than half (53%) of the sample farmers transplanted the rice crop and 47% practiced wet direct seeding (WDS). These two groups of farmers are almost equally distributed between pump and gravity systems. Farmers who direct-seeded the rice crop used more water than those who transplanted, both during land preparation and during the crop growth period from crop establishment to harvest (Table 3). Cumulative water depth under direct seeding was 1,686 mm vis-à-vis

Table 2. Cumulative depth of water applied and number of irrigations, disaggregated by water delivery system.

Water delivery system	Cumulative depth of water (mm)			Number of irrigations		
	Land preparation	Crop establishment to harvest	Total water depth	Land preparation	Crop establishment to harvest	Total number of irrigations
Gravity	342	1,125	1,466	3.8	17.0	20.8
Pump	288	973	1,262	3.1	13.1	16.3
P value	0.46	0.39	0.33	0.37	0.05	0.05

Table 3. Cumulative depth of water applied and number of irrigations, by method of crop establishment.

Method of crop establishment	Cumulative depth of water (mm)			Number of irrigations		
	Land preparation	Crop establishment to harvest	Total water depth	Land preparation	Crop establishment to harvest	Total number of irrigations
Wet direct-seeded	343	1,342	1,686	3.9	17.4	21.4
Transplanted	290	787	1,078	3.1	13.0	16.0
P values	0.46	<0.01	<0.01	0.23	0.02	0.02

just 1,078 mm for transplanting. This difference is statistically significant at the 1% level. A similar pattern holds for the number of irrigation events. The main reason for this result is the longer field duration of direct-seeded crops. Although direct-seeded rice can be harvested 1 week earlier than transplanted rice, transplanted rice is placed in the field nearly 1 month after crop establishment (average seedling age at transplanting in our sample is 27 days). Even though our data do not measure water consumption per se (rather, the degree of flooding), our results seem inconsistent with the findings of Tuong and Bhuiyan (1994) and Tabbal et al (2002) that WDS rice consumed less water. However, our data refer to the actual farmers' practice while the other studies are the results of on-farm experiments. It must be noted, however, that these practices could be site-specific.

To summarize, farmers who have access to gravity-flow water tend to keep their fields more flooded than farmers who pump, and farmers who direct-seed their crop have a greater cumulative depth of water applied because their crops are in the field for a longer growth duration. To examine this variation in water use across farms in more detail, a multivariate regression equation was estimated with the cumulative depth of water as the dependent variable and the following factors as explanatory variables: (1) rainfall—the total amount of rainfall received by each farm from land preparation to harvest, (2) solar radiation—the total amount of solar radiation received by the crop from crop establishment to harvest, (3) a dummy variable for crop establishment method, (4) dummy variables for three of the four soil textures (clay, clay loam, sandy loam, and sandy), and (5) dummy variables for two of the three water-delivery systems (gravity, pump owners, and pump renters). The same regression was also estimated using the number of irrigations as the dependent variable.

The results of the regression are similar to those of the earlier discussion. The sign on the dummy variable for gravity was positive (significant at the 10% level in the regression on number of irrigations). The sign on the dummy variable for transplanting was negative (statistically significant at the 10% level in the regression on cumulative water depth), indicating that farmers who practiced direct seeding had a greater cumulative water depth. We also tested for a difference between pump renters and pump owners, but did not find any statistically significant difference between the two groups in their water-use patterns. Other variables were generally not statistically significant, so the regression results are not presented here.

Comparative economic performance

There is a general belief that using pumps to irrigate the rice crop is quite expensive and will greatly affect the profitability of rice production. This section compares the performance of rice production using gravity water or pumped water first in terms of physical quantities of inputs and outputs and second in monetary terms.

Yield and input use

The two groups of farms produced nearly identical mean yields of 6.7 and 6.8 t ha^{-1} for pump and gravity systems, respectively (Table 4).[1] This suggests that the lower number of irrigations and reduced level of flooding in the pump system do not result in a yield penalty. However, to examine this aspect in more detail, we tried a more sophisticated statistical approach by estimating a linear production function with yield as the dependent variable and several independent variables measuring biophysical parameters and input quantities: cumulative water depth, rainfall, solar radiation, fertilizer (N, P, and K separately), herbicide, seed, preharvest labor, water source (surface or ground), soil texture (dummy variables for clay, clay loam, silty loam, and sand), and crop establishment technique (dummy variables for transplanting and wet direct seeding). The regression coefficient on cumulative water depth was negative but not statistically significant, implying that, within the bounds of variation in this sample, the degree of flooding did not substantially and consistently affect yield. Only two of the independent variables had statistically significant coefficients: those on solar radiation (positive sign) and the dummy for sandy soil texture (a negative sign relative to silty loam).

Table 4. Yield and input use disaggregated by water-delivery system.

Item	Gravity system	Pump system
Yield (t ha^{-1})	6.8	6.7
Area planted (ha)	1.90	1.42
Fertilizer use (kg ha^{-1})		
N	147.0	152.3
P	20.0	22.9
K	15.3	15.8
Seeds (kg ha^{-1})	160	182
Pesticides (kg ai ha^{-1})		
Insecticide	0.29	0.20
Herbicide	0.60	0.60
Molluscicide	0.11	0.12
Labor use (8-h labor-day ha^{-1})		
Land preparation	8.2	8.2
Crop establishment	9.9	14.6
Crop care	16.8	17.6
Harvest and postharvest	24.6	25.4
Total labor use	59.5	65.8

[1]Yield data are calculated using farmers' estimates of production and area for the whole parcel at field moisture content levels shortly after harvest (estimated to be about 20–24% MC).

Nitrogen fertilizer use is almost equal in the two systems as well: 152 kg N ha^{-1} for pump systems and 147 kg N ha^{-1} for gravity systems. There was also no significant difference in the amount of pesticide applied to the crop. Labor use for pump systems (66 d ha^{-1}) was higher by about 7 days compared with gravity systems (59 d ha^{-1}), although the difference is not statistically significant. The amount of labor is almost equal in magnitude for all major farm activities except for crop establishment, for which labor use is higher in the pump system by about five days. A slightly bigger proportion of transplanting relative to direct seeding in the pump system compared to farms in the gravity system could explain this difference. All in all, these results imply that, in terms of the physical quantity of output (yield) and inputs, there is little difference between farms irrigated by pumps and farms irrigated by gravity surface flow.

Profitability of rice production

Costs of rice production. Total costs as presented here include all costs of production from the day the farm is initially irrigated to facilitate land preparation up to the day the paddy is sold or stored for future consumption. We also include data on land rents. However, we did not collect data on depreciation of farm implements such as tractors, sprayers, plows, and harrows. The cost of family labor is imputed based on the wage rate paid by the farmer for hired labor, that is, we assume that there is an opportunity cost for family labor.

Water costs include the irrigation fee actually paid by farmers to the NIA in the case of gravity systems (not the amount they are charged by the NIA, which may be different from the amount paid). As noted earlier, there are some farmers we classified under the gravity system who occasionally pump water to irrigate their fields: for these farmers, there are some pumping costs as well, but they are minor compared with similar costs for farmers whose major water-delivery system is the pump system (Table 5). For farmers whose dominant water-delivery system is a pump, water costs consist of fuel costs and pump rental (and imputed pump rental for pump owners) plus the appropriate fee paid to the NIA. According to NIA rules, farmers who pump water from the irrigation canal should pay 50% of the irrigation fee charged to gravity-system users. However, farmers who pump from underground sources are not required to pay fees for using this water.

For the gravity system, the major cost component is labor (Table 5). For the pump system, however, material input costs constitute the biggest share of total costs, accounting for 51% of the total. The high material input costs of the pump system are due primarily to high water costs, which amount to \$183 ha^{-1}. In contrast, water costs for gravity systems amount to just \$23 ha^{-1}.

About two-thirds of the farmers in our sample own their land outright or are paying off a bank loan to own the land in the future. In either case, they do not pay any rental to a landowner. The other one-third of the farmers in our sample are predominantly leaseholders. These farmers pay a fixed rent (in pesos or in rice) every year or every season directly to the landowner (share tenancy is technically illegal in the Philippines, although one farmer in our sample is a share tenant). Among 19 lease-

Table 5. Comparative economic performance of sample farms by water-delivery system.

Item	Gravity system	Pump system
	(US$ ha^{-1})	
Gross return	1,392	1,394
Material input costs	265	450
Fertilizer	94	100
Pesticide	31	35
Seeds	49	55
Water costs	23	183
Irrigation fee	18	6
Fuel costs	2	40
Pump rental	3	137
Power costs	56	59
Miscellaneous costs	13	17
Labor costs	327	352
Hired labor	240	278
Imputed family labor	87	74
Land rent	115	76
Total costs	707	878
Net return to land and management	800	593
Net return to management	685	517

holders in our sample, 11 used gravity flow as the dominant water-delivery system, whereas eight used a pump. Land rents were on average $115 where gravity flow was the dominant delivery system and $76 where pumps were the primary means of delivering water to the field. Thus, farmers who must pump to obtain water pay a lower land rent, although the lower rent compensates for only about 24% of the higher water costs.

In our cost data in Table 5, we include land rent for all farmers, whether the rent is actually paid or not. This is because farmers who own their land have the option of renting it out to others; the imputed land rent measures their opportunity cost of farming their own land. Except for the costs of irrigation water and land rents, all other costs of production are similar in magnitude for the two systems.

Effects of pumping on farm profit. Farm profit is calculated by subtracting the total costs of production from gross returns (total value of production). Gross returns were estimated by multiplying yield (t ha^{-1}) by the price per kg of paddy that the farmers received when they sold their produce. As stated earlier, yield in the two systems is nearly identical. Similarly, the mean price received by farmers for their paddy is almost equal: $0.202 kg^{-1} in the gravity system and $0.205 kg^{-1} for the pump system. This results in almost equal mean gross returns for the two groups of farms: $1,392 ha^{-1} and $1,394 ha^{-1} for gravity and pump systems, respectively. But, since the costs of production differ between the two groups, the net returns received by farmers using pumps are lower than those using a gravity system. The net return to land and management for pump users is about \$593 ha^{-1}, much lower than the \$800 ha^{-1} net return realized by farmers using the gravity system. Nevertheless, net returns are still substantially positive in both systems. It should be noted that part of the reason for the substantial net returns in these systems is the fact that rice prices are much higher in the Philippines than in neighboring countries, which inflates the gross returns received by farmers. In other countries, gross returns would be lower, and the net returns to land and management for pump users could be much lower.

Because land rent is higher for farmers with access to gravity-flow water, net returns to management show less discrepancy between pump and gravity systems than do net returns to land and management combined. Nevertheless, net returns to management are still substantially higher for gravity-system farmers than for pump-system farmers. This differential persists because land rental markets are not active in rural areas of the Philippines and the terms of leaseholds are usually subject to government regulations, at least to some extent. In fact, in many cases, government officials can be actively engaged in mediating between the leaseholder and the landowner. If private land rental markets without government intervention were more active in the rural Philippines, presumably net returns to management would be more similar in the two systems, as competition for scarce land with access to water from a functioning gravity irrigation system would drive rents up in these areas, thereby reducing the returns to management.

Summary and conclusions

The conjunctive use of surface water and groundwater is found to be economically feasible in areas where gravity-flow surface water is inadequate to meet farmers' demand for water. In spite of the high cost of pumping water, pump users are still getting a substantial amount of farm profits from rice production, although profits are lower in comparison with those obtained on farms with good access to a surface gravity system. If irrigated rice is profitable even when water costs are relatively high, this suggests that the NIA's policy of encouraging groundwater use in the tail end of systems may be a sensible policy to ensure adequate water supplies for larger numbers of farmers. However, this conclusion is not necessarily applicable to other countries because paddy prices in the Philippines are very high compared with those in neighboring countries (Moya et al 2002). If paddy prices are lower, it will be more difficult for rice production to remain profitable when pumping costs are incurred.

In general, there are no significant differences in yield or input use between farms irrigated by pumps and the surface gravity system, with the exception of water use. Farms that rely on pumping irrigate fewer times and have a lower degree of flooding (by about 14% during crop growth). Land rents are higher for farms with good access to gravity-flow water compared with farms that rely heavily on pumping.

However, it is important to note that the findings of this study are applicable only to this specific location. Since pumping has become widespread in Asian rice cultivation in recent years, more studies on the economic and water management effects of pumping in different areas would provide useful information.

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Notes

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Estimation of spatially distributed evapotranspiration through remote sensing: a case study for irrigated rice in the Philippines

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Water for agriculture in Asia is increasingly scarce and ways must be sought to optimize the use and efficiency of irrigation systems, especially in water-consuming irrigated rice systems. This requires an understanding of the water balance at different spatial scales of the irrigation system. An important component of the water balance is actual evapotranspiration (ET_a). This paper reports on the use of remote sensing to estimate spatially distributed ET_a from irrigated rice in the Upper Pampanga River Integrated Irrigation System (UPRIIS) in Central Luzon, Philippines. The surface energy balance algorithm for land (SEBAL) was used to compute ET_a from three Landsat 7 ETM+ images acquired during the second part of the crop growth period in the dry season of 2001. Ground-truth data for the calibration of SEBAL were obtained during satellite overpass. The outputs of the SEBAL computations were georeferenced maps and frequency distributions of daily ET_a on the days of satellite overpass. The calculated ET_a values were some 6% lower than potential rice evapotranspiration values calculated with the modified Penman Monteith method using weather data from two meteorological stations in the area. It was concluded that SEBAL provides realistic estimates of actual evapotranspiration of irrigated rice over spatially extended areas in the tropics.

Water resources for agriculture are becoming increasingly scarce and ways must be sought to optimize the use and efficiency of irrigation systems (Postel 1997). This is especially true for irrigated rice systems that account for more than 50% of total irrigation water volume in Asia (Barker et al 1999). Rice is the most important staple in Asia, where it provides 35–80% of total calorie uptake (IRRI 1997). More than 75% of the rice supply comes from 79 million ha of irrigated land. Thus, the present and future food security of Asia depend largely on the irrigated rice production system. The optimization of irrigation systems requires knowledge on the water balance: the amounts of inputs (rainfall, irrigation, run-on, lateral inflow) and outputs (evapotranspiration, percolation, seepage, runoff, drainage). Moreover, this knowledge should be available at different spatial scale levels. Irrigation systems usually consist of a complex network of irrigation and drainage canals with a considerable amount of water reuse (e.g., Zulu et al 1996). Water outflows from one particular section of an irrigation system may be reused in another section by damming drains or pumping water from creeks (or both). Therefore, several studies are focusing attention on the quantification of the water balance of irrigation systems at different scale levels (e.g., Dong et al 2001, Keller et al 1996, Seckler 1996). The measurement of surface in- and outflows is relatively straightforward (Dong et al 2001). However, the measurement of evapotranspiration (ET) poses more problems. There are many methods to estimate ET using meteorological data (see Allen et al 1998, for overview), but these are based on point data, which do not provide good estimates of ET for larger areas. Moreover, most of these methods estimate potential or reference ET and not actual ET. The problem of actual ET estimation over large areas can be solved by using imagery obtained with satellite remote sensing. Bastiaanssen (1995) and Bastiaanssen et al (1998) developed the thermodynamically based surface energy balance algorithm for land (SEBAL) to estimate actual ET from agricultural areas using optical satellite imagery. However, SEBAL has not yet been tested for rice-based cropping areas in the tropics. In this paper, we present results of the application of SEBAL to estimate ET in a multiscale water-balance study of an irrigated rice production system in the Philippines. The specific objectives of the study reported here are to evaluate the performance of SEBAL in tropical irrigated rice areas and to compute the spatial variation in ET within a large-scale surface irrigation system.

Materials and methods

Study area

The Upper Pampanga River Integrated Irrigation System (UPRIIS) in Central Luzon (Fig. 1), Philippines, covers an area of 102,000 ha and is divided into four districts. It gets its water from a combination of various run-of-the-river flows and the Pantabangan reservoir. There is a dry season from November to April and a wet season from May to October. The average annual rainfall is about 1,900 mm, of which 90% falls in the wet season (Tabbal et al 2002). Soils are Vertisols, Entisols, and Inceptisols (USDA classification) and have typically silty clay, silty clay loam, clay loam, and clay textures. The average groundwater table depth is 0.5 m in the wet season and 1.5 m at the end of the dry season, although locally it can come up to 0.1 m and go down to deeper than 5 m. Double cropping of rice is the most common land use and UPRIIS produces an average of 63 million tons of rice every year. However, where water is scarce, upland crops such as onion, tomato, watermelon, and maize are grown in the dry season.

The water-balance study focuses on district 1, which has a total area of 28,205 ha, including rice fields, upland crops, vegetables, roads, settlements, and water bodies. District 1 is bounded by the Talavera River to the east and the Ilog Baliwag River to the west, and consists of an upper part, called the Talavera River Irrigation System-Lower (TRIS-L), and a lower part, called the Santo Domingo Area (SDA). The TRIS-

L receives its water directly from main diversion canal 1. Part of the water from the main diversion canal is diverted into the Sapang Kawayan Creek, which also collects drainage water while it traverses TRIS-L. In the lower part of TRIS-L, the De Babuyan check dam raises the water level in the Sapang Kawayan Creek and the water is diverted into the Santo Domingo main canal that irrigates the SDA. About 20% of the farmers use pumps to draw water from shallow tubewells (or from drains and creeks) for supplementary irrigation (IRRI, unreported data). For the multiscale analysis, the whole of district 1 was divided into five sections, based on the possibilities to monitor surface water in- and outflows (Table 1, Fig. 1).

TRIS-L has 48 farmer-irrigator associations (FIAs), with an average size of 233 ha. Twelve small check dams capture internal drainage water. In 2001, the farmers did not face a water shortage and planted rice according to the recommended cropping schedule. Only a few farmers located in the tail end of lateral F (near SDA) could not grow rice in the dry season because of a water shortage.

SDA-A is in the upper part of SDA. There are five FIAs with an average size of 175 ha. SDA-A receives water from lateral A and B and from two creeks coming out

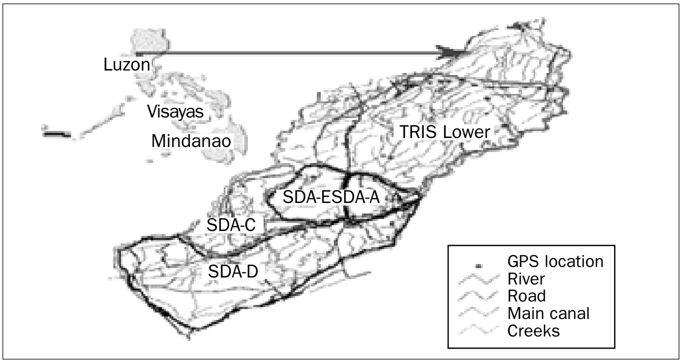

Fig. 1. District 1 and the five irrigation sections studied in the UPRIIS.

Table 1. Sizes of the irrigation sections studied and their area under rice in the 2001 dry season.

Section	Area (ha)	% area of district 1	Rice area (ha)	% rice area[a]
District 1	28,205	100	17,045	60
TRIS-L	11,239	40	8,599	77
SDA[a]–A	1,513	5	877	58
SDA–B	2,240	8	1,311	59
SDA–C	3,011	11	1,911	64
SDA–D	10,201	36	4,347	43

[a]Santo Domingo Area.

of TRIS-L. The De Buasao check dam is the origin of lateral A-Extra (A-x), which also supplies water to the lower part of SDA-A and to the upper part of SDA-D. The farmers far away from the main canal depend relatively more on shallow tubewells for additional irrigation water than the farmers close to the beginning of the main canal.

SDA-B is the second smallest area. The major source of water is lateral C, sublaterals of lateral B, and two creeks getting water from the Ilog Baliwag River. There are six FIAs with an average size of 373 ha. Water shortage forces farmers to get water either through pumping or by using illegal inlets along the Santo Domingo main canal. The Pajo check dam captures drainage water from farmers upstream and serves as a major source of water for SDA-C.

SDA-C is in the lower portion of the SDA. The laterals D, E, E-X, F, and G and two creeks (Pajo and Labong) are the main sources of water. There are seven FIAs with an average size of 273 ha. All farmers in SDA-C depend on pumping for an additional supply of water. Normally, the farmers get surface water only when the upstream farmers don't need it. The cropping pattern depends totally on the availability of irrigation water and rice planting is about 2–3 weeks later than in TRIS-L. Santa Rita is the only check dam in SDA-C that captures drainage water in small creeks and serves as a major source of water for SDA-D.

SDA-D is in the lowest part of SDA. There are 22 FIAs with an average size of 198 ha. Because of a water shortage in the canals, farmers do not grow rice in the dry season. Also, the National Irrigation Administration does not encourage farmers to grow rice because the dominant soil type is sandy loam, which has a high percolation rate. Only the farmers located near the canals and creeks plant rice using pumps as an additional source of water.

Satellite data

Three Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) images were obtained from the second part of the dry season 2001: 16 April, 2 May, and 18 May. The ETM+ instrument of Landsat 7 is of the fixed "whisk-broom" type, having seven multispectral bands and one panchromatic band (Table 2). Orbiting at an altitude of 705 km, it registers spectrally filtered radiation from the sun-lit Earth in a 183-km-wide swath. Level 1G products are radiometrically and geometrically corrected to user-specified parameters, including output-map projection, image orientation, pixel (grid-cell) size, and resampling kernel. The gain and offset values for the images are provided in the header file. The georeferencing of the images was done using the coordinates provided in the header file in UTM/WGS84/Zone 51.

SEBAL-ET estimation

SEBAL is a thermodynamically based model, which partitions between sensible heat flux and latent heat of vaporization flux. A full explanation of SEBAL is beyond the scope of this paper (see Bastiaanssen 1995, Bastiaanssen et al 1998, Tasumi et al 2000). Hafeez and Chemin (2002) give a detailed description of the calculation pro-

Table 2. Characteristics of the Landsat 7 ETM+ sensor.

Subsystem	Number of bands	Spectral range (mm)	Spatial resolution (m)
VNIR	4	0.45 up to 0.90	30×30
SWIR	2	1.55 up to 2.35	30×30
TIR	1	10.4 to 12.5	60×60
PAN	1	0.50 to 0.90	15×15

cedure followed in the application of SEBAL in this study. Preprocessing parameters required for SEBAL included the normalized difference vegetation index (NDVI), emissivity, broadband surface albedo, and surface temperature. The NDVI was calculated from the spectral reflectance of the red (band #3) and near-infrared (band #4) channels using equations developed by Bandara (1998). The surface emissivity was computed from the NDVI following the method of Van de Griend and Owe (1993). The broadband albedo was calculated using weighing factors of all visible, near-infrared, and short-wave infrared bands. The radiant temperature at the top of the atmosphere was computed from the inverse Planck function using the outgoing spectral radiance in band 6. Assuming that the internal calibration of the thermal bands of ETM+ is satisfactory, the calibration gain and offset provided with the L1G data can be used to produce the radiant temperature values. A standard thermal surface emissivity adjustment was used to adjust the surface temperature taking into account graybody properties of the surface.

All essential meteorological data for solving SEBAL, such as (hourly) temperature, humidity, wind speed, and solar radiation at the time of satellite overpass, were collected from two weather stations in district 1: PAGASA at Muñoz (15°43′N, 120°54′E) and PhilRice at Maligaya (15°39′N, 120°53′E). Other data collected for SEBAL calibration were soil temperature, surface-water temperature, and various vegetation parameters across district 1.

The daily actual evapotranspiration is calculated in SEBAL from the instantaneous evaporative fraction and the daily average net radiation. The latter has to be transformed from W m^{-2} to mm d^{-1} by inserting the temperature-dependent latent heat of vaporization equation into the main equation:

$$ET_a = \Lambda \times \left[R_{n24} \times \left((2{,}501 - 0.002361 \times T_0) \times 10^6\right)\right] \text{ (mm d}^{-1}\text{)} \qquad (1)$$

where ET_a is the actual daily ET (mm d^{-1}), Λ is the evaporative fraction (-), R_{n24} is the average daily net radiation (W m^{-2}), and T_0 the surface temperature (°C). The evaporative fraction is computed from the instantaneous surface energy balance at the moment of satellite overpass for each pixel:

$$\Lambda = \frac{\lambda E}{R_n - G_0} = \frac{\lambda E}{\lambda E + H_0} \quad (-) \qquad (2)$$

where λE is the latent heat flux (W m^{-2}), R_n is the net radiation absorbed or emitted from Earth's surface (W m^{-2}), G_0 is the soil heat flux (W m^{-2}), and H_0 is the sensible heat flux (W m^{-2}). λ can be interpreted in irrigated areas as the ratio of actual over potential evapotranspiration.

Conventional ET estimation

Daily meteorological data were collected from the PAGASA and PhilRice weather stations and used to calculate the reference evapotranspiration, ET_0, using the modified Penman Monteith equation (Allen et al 1998). The ET_0 was converted into potential rice evapotranspiration, ET_c, by multiplying by the crop coefficient K_c ($ET_c = K_c \times ET_0$). Based on the actual cropping calendar, the crop coefficients K_c for rice were 0.95 on 16 April, 0.85 on 2 May, and 0.75 on 18 May.

Results and discussion

Outputs of SEBAL are pixel-based, daily-average estimates of actual evapotranspiration (ET_a). Figure 2 gives a map of ET_a for the whole of district 1 on 18 May. Low values of ET_a indicate areas where rice (or other crops) has been harvested and the soil is bare or covered with stubble. High values of ET_a indicate areas where rice (or another crop) is still in the field and actively transpiring.

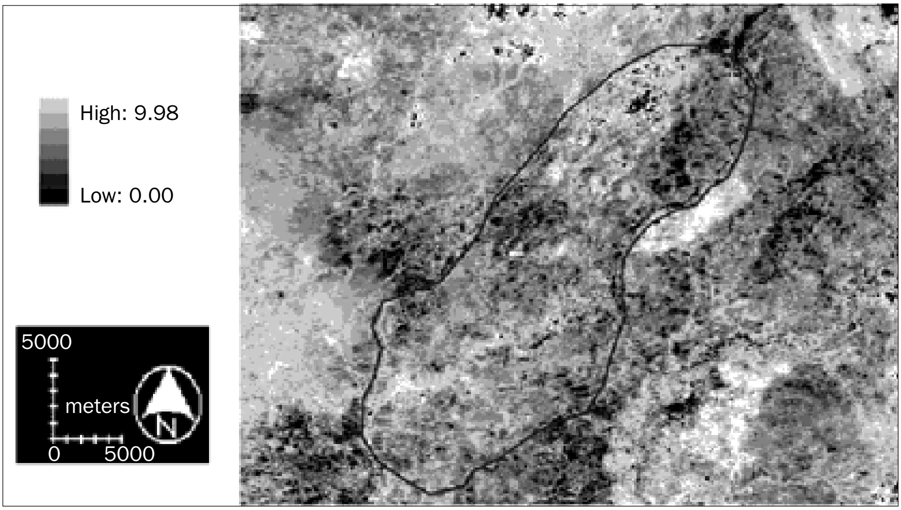

Fig. 2. Actual evapotranspiration, ET_a, for district 1 on 18 May 2001.

Figure 3 gives the frequency distribution of the pixel-based ET_a values of district 1 for all three days of satellite overpass. The ET_a ranges from 0.2 to 6.8 mm d^{-1} on 16 April, from 0.2 to 7.4 mm d^{-1} on 2 May, and from 0.2 to 7.3 mm d^{-1} on 18 May. All three frequency distributions of ET_a are mono-modal with peaks of 5.9 mm d^{-1} on 589 ha of area on 16 April, 6.4 mm d^{-1} on 589 ha on 2 May, and 6.6 mm d^{-1} on 589 ha on 18 May. On 16 April, the land use was relatively homogeneous in the whole of district 1 because rice was the major crop. On 2 May, there were two main land covers: bare fields after the harvesting of rice in the upper part of district 1 (TRIS-L) and ripening rice fields in the lower part of district 1 (SDA). On 18 May, the land cover was totally changed and only 20% of the lower part of SDA was still under rice, whereas the farmers in TRIS-L had sown short-duration upland crops such as watermelon.

Table 3 shows the area-mean ET_a of district 1 and of the five irrigation sections. Note that each value is calculated as the average from all pixel-based ET_a values in the area under consideration, and hence includes rice fields, other crops, forest, roads, settlements, and water bodies. On 16 April, when 90% of the area was estimated to be under rice, the area-mean ET_a values were statistically not significantly different from each other (at the 5% level) for all irrigation sections and district 1 as a whole. On 2 May, the differences among the areas were relatively large and can be explained by the fact that land use was the most diverse among all three dates. Some rice fields were harvested and had either stubble or tilled soil, some fields still had standing rice, and other fields still had a cover of upland crops. On 18 May, there were statistically two groups of areas: SDA-A, SDA-B, and SDA-C versus SDA-D and TRIS-L. The reason for the relatively high ET_a in SDA-D and TRIS-L was that farmers in these areas had started planting upland crops such as watermelon that actively transpired.

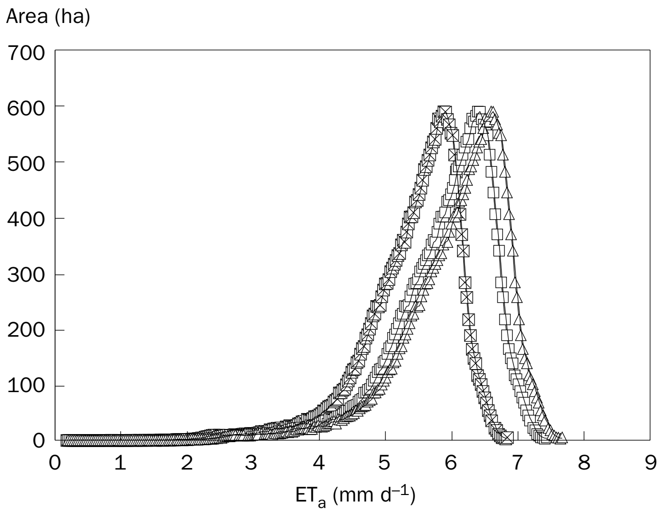

Fig. 3. Frequency distribution of ET_a in district 1 in terms of area covered on 16 April (⊠), 2 May (□), and 18 May (△).

The area-mean ET_a of the whole of district 1 was always statistically the same as those of its constituting subareas, except for SDA-A on 2 May.

Table 4 gives the measured pan evaporation, E_{pan}, and the calculated reference evapotranspiration, ET_o, and potential rice evapotranspiration, ET_c, at the PAGASA and PhilRice weather stations. For comparison, the SEBAL-calculated ET_a of all rice pixels within a 10-km radius from the weather stations is also given. Except on 2 May, the E_{pan} values were about the same at both stations. On 16 April and 2 May, ET_o was considerably lower than E_{pan}, whereas on 18 May it was only a little bit lower (0.1–0.2 mm d^{-1} lower). Because rice was in the ripening phase on all three dates of observation, their K_c values were smaller than 1 and ET_c was lower than ET_o.

Table 3. Area-mean ET_a (mm d^{-1}) for each irrigation section and district 1 on 16 April, 2 May, and 18 May.

Section/date	16 April	2 May	18 May
District 1	3.5 a[a]	3.8 abc	3.9 ab
TRIS-L	3.5 a	3.7 bcd	4.3 a
SDA–A	3.5 a	3.4 d	3.8 b
SDA–B	3.4 a	4.2 a	3.8 b
SDA–C	3.4 a	3.7 cd	3.6 b
SDA–D	3.7 a	4.1 ab	4.2 a

[a]Similar letters indicate that means are statistically the same at 95% confidence level.

Table 4. Class-A pan evaporation (E_{pan}), reference evapotranspiration (ET_o), and potential rice evapotranspiration (ET_c) at the PAGASA and PhilRice weather stations, and actual evapotranspiration (ET_a) of rice pixels surrounding the meteorological stations (all in mm d^{-1}).

Meteorological station Date		PAGASA	PhilRice
16 April	E_{pan}	6.8	6.8
	ET_o	5.8	5.8
	ET_c	5.5	5.5
	ET_a	5.2	
2 May	E_{pan}	6.8	7.2
	ET_o	5.9	5.7
	ET_c	5.1	4.9
	ET_a	4.7	
18 May	E_{pan}	7.0	6.9
	ET_o	6.8	6.8
	ET_c	5.1	5.1
	ET_a	4.9	

On all three dates, the SEBAL-calculated actual ET (ET_a) was lower than the potential ET (ET_c).

Conclusions and future directions

Optical satellite imagery and the SEBAL algorithm provided estimates of spatially distributed actual evapotranspiration on the days of satellite overpass. The spatial patterns could generally be explained by observed cropping patterns in the field. For pixels assumed to be under (ripening) rice, the estimated actual evapotranspiration was on average 6% lower than the potential evapotranspiration calculated using the modified Penman Monteith equation at nearby weather stations. This can be explained by the fact that, during ripening of rice, farmers drain the fields (to promote ripening) so that the crop experiences drought conditions and closes its stomata, thereby reducing its transpiration rate. Moreover, the evaporation from the underlying, drying soil surface is lower than that from a ponded water layer under potential evapotranspiration conditions. It is concluded that the SEBAL algorithm provided realistic estimates of actual evapotranspiration of irrigated rice in the tropics.

Differences in actual evapotranspiration among subregions of the irrigation district were significant at the end of the growing season only when rice got harvested and new crops got planted. Differences were caused by differences in crop scheduling. It can be expected that differences will also occur in the beginning of the growing season when differences in availability of irrigation water among subregions will result in different planting times of rice. In the next steps of our study, estimates of actual evapotranspiration will be made for each day of the season and used to calculate the water balance of district 1 at different spatial scales.

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Notes

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