Management strategies for saving water and increase its productivity in lowland rice-based ecosystems

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Abstract

Traditional lowland rice production in Asia requires much water: it consumes more than 50% of all irrigation water used in Asia. Water resources are, however, increasingly getting scarce and expensive. The supply of water for irrigation is endangered by declining water quality, declining resource availability, increased competition from other users, and increasing costs. Rice is especially sensitive to declining water availability since it requires more water than any other food crop and it has relatively low water-use efficiency. At the farm level, water inputs can be reduced by decreasing the relatively large and unproductive losses from seepage, percolation, and evaporation. In the last decade, researchers have studied and developed a number of water-saving irrigation technologies such as saturated soil culture and alternate wetting and drying (AWD) that can drastically diminish these losses. Under these technologies, yields may decline, but they have demonstrated that they save water and increase water productivity. Unfortunately, adoption by farmers is low because extension activities are lacking. Compared with heavy investments needed to develop new water resources, the adoption of water-saving technologies by farmers is low-cost and has great potential to save water. In 2001, we initiated a farmer-participatory project called 'Technology Transfer for Water Saving (TTWS)' to transfer and promote AWD among farmers in the Philippines. The TTWS was conceived to develop and implement a framework for transfer, adaptation, and adoption of knowledge on water-saving technologies. Actual measurements from farmers' fields showed that AWD had the same yield as farmers' practice and that, on average, it saved 16–24% water and 20-25% costs. Group factors identified for successful collective action to facilitate AWD adoption are group size, service area, profitability, high level of excludability, enhancement of existing social capital, strong leadership to deal with free riders, and close linkages

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with local governments.

Aerobic rice is a new concept of growing rice using less water: high-yielding rice is grown in nonpuddled aerobic soil using supplementary irrigation just like upland crops. Farmers in China and Brazil where water is scarce or costly are pioneering this system. A group of first-generation elite aerobic varieties have already been developed and released in temperate northern China, replacing traditional lowland rice on some 190,000 ha water-short irrigated area and traditional upland crops on low-lying flood-prone areas. IRRI started an aerobic rice program for the tropics in 2001. The program aims to develop (1) aerobic rice varieties for tropical condition; (2) integrated management practices for water, weeds and nutrients; and (3) sustainable and environment-friendly systems. Objective 1 is being addressed through varietal breeding, screening, and yield trial evaluations. Objectives 2 and 3 are being addressed through field experiments and farmer-participatory R&D. We have now tested and selected three varieties with average yields of 4.4 t ha^{-1} in the wet season and 3.4 t ha^{-1} in the dry season in farmers' fields. Yields during the wet season were more stable than those in the dry season. Some farmers got extremely high (>6 t ha^{-1}) and extremely low (<1 t ha^{-1}) yields in the dry seasons. However, more aerobic rice varieties are needed and understanding management strategies is essential if this system is going to be successful. Through the adoption of water-saving irrigation technologies, rice land will shift from being continuously anaerobic to partly or even completely aerobic. This will have major consequences on sustainability, such as weed, pest, and disease ecology and nutrient and soil organic matter dynamics.

Keywords: Aerobic rice; Alternate wetting and drying; Technology transfer for water savings; Water management strategies

1. Introduction

Rice is the major staple food in Asia, where about 92% of the world's rice is produced and consumed (Maclean et al., 2002). More than 75% of the world's rice supply comes from 79 million ha of irrigated land in Asia. Thus, the present and future food security of Asia depends largely on the irrigated rice production system. However, this system is a major user of fresh water. In Asia, irrigated agriculture accounts for 90% of total diverted fresh water, and more than 50% of this is used to irrigate rice (Barker et al., 1999). About 80% of all rice is being produced under lowland conditions: puddled and saturated soils with a continuous layer of ponded water.

The water requirements for lowland rice are particularly high compared with other (upland) crops because of the water needs for land preparation (soaking, puddling), the continuous seepage and percolation losses caused by the standing water layer, and the high evaporation losses from the water layer. To produce just one ton of rice requires between 2-3 Olympic-sized swimming pools full of water. Throughout the centuries, these high water requirements have been taken for granted, but recently, the availability of water for irrigation is increasingly scarce (Gleick, 1993; Postel, 1997). The reasons are diverse and location-specific, but include decreasing resources, decreasing quality (chemical pollution, salinization) and increased competition from other sectors such as urban and industrial users and natural reserves or ‘environmental’ water. It is expected that wet season irrigated rice areas in north China (2.5 million ha), Pakistan (2.1 million ha) and north and central India (8.4 million ha) will experience ‘physical water scarcity’ by 2025 (Tuong and Bouman, 2002). In addition, most of the approximately 22 million ha dry season irrigated rice areas in South and Southeast Asia will suffer ‘economic water scarcity’ in 2025.

Already, water scarcity prevails in certain rice growing areas. In the Philippines, some 61% of the 3.4 million ha of rice land is under irrigation, with the majority of the production coming from the rice bowl in central Luzon (Maclean et al., 2002). Irrigation is provided by gravity systems and shallow and deep tubewells. However, the availability of water for irrigation has declined in the last decade(s). Water from the Angat reservoir in Bulacan Province is increasingly diverted toward the Greater Manila Area (Pingali et al., 1997), water in the Agno River Irrigation System in Pangasinan Province is polluted with sediments and chemicals from mining activities upstream (Castañeda and Bhuiyan, 1993), and many irrigation systems were destroyed and clogged by the earthquakes of 1990 and the Mount Pinatubo eruption in 1991 (NIA, 1996). Because of its dense population and close proximity to the capital Manila, rice production in central Luzon is of strategic importance to food security and poverty alleviation. The government of the Philippines, through its National Irrigation Administration (NIA), is dedicated to maintain and enhance irrigation water availability by infrastructural development and maintenance and by the propagation of water-saving irrigation technologies (NIA, 1996).

The decreasing availability of water for irrigated rice threatens food security in Asia in general and the livelihood of farmers in particular. Also, the increasing scarcity of water means that the costs of its use and resource development are increasing dramatically (Postel, 1997; Rosegrant, 1997). Therefore, researchers have been looking for ways to decrease water use in rice production and increase its use efficiency. Though water use can be optimized at scale levels from field to farm, irrigation system, watershed and entire river basins, a fundamental approach is to save water at the field level where water and the rice crop interact. This is also the scale level that concerns rice farmers most. The past decades, much research has been done at the field level and various technologies have been proposed that save water and increase its productivity while maintaining high yields (e.g., Sandhu et al., 1980; Mishra et al., 1990; Li, 2001). In the Philippines, pioneering research has been done by the International Rice Research Institute (IRRI; Bhuiyan et al., 1995; Tabbal et al., 1992; Tuong, 1999; Bouman and Tuong, 2001) and PhilRice (de Dios et al., 2000). Despite the good results obtained in research, however, very little attention has been paid to the dissemination, extension and adoption of the developed technologies among farmers in the Philippines. At the moment, it is not well known how farmers actually manage their water and to what extent they are aware of water-saving technologies. It is generally assumed that rice farmers in Asia have gotten used to the idea of continuously flooding their fields for much of the growing period. This practice is tied up with weed control, ease for transplanting and on the belief that reducing the amount of water will be harmful to the plant. To bridge the gap between research on water-saving technologies and adoption by farmers, IRRI, PhilRice and NIA initiated in 2001 a special project called ‘Technology Transfer for Water savings (TTWS)’ in rice production. This paper describes some strategies to cope with the decreasing water supply at the farm or field inlets. It also presents the results of the water savings project in the Philippines.

2. Water management strategies to reduce water input

Large reductions in water input can potentially be realized by reducing the unproductive seepage and percolation (SP) and evaporation flows (Tuong, 1999; Bouman and Tuong, 2001). There are basically two ways to do so: (1) increasing the resistance to water flow in the soil and (2) decreasing the hydrostatic water pressure and the duration of flooded water. The resistance to water flow can be increased by changing the soil physical properties. Cabangon and Tuong (2000) have shown the beneficial effects of additional shallow soil tillage before land preparation to close cracks that cause rapid bypass flow at land soaking. Thorough puddling results in a good compacted plow soil that impedes vertical water flow (De Datta, 1981). Soil compaction using heavy machinery has been shown to decrease soil permeability in northeast Thailand in sandy/loamy soils with at least 5% clay (Sharma et al., 1995). Finally, researchers have even experimented with introducing physical barriers underneath paddy soils such as bitumen layers and plastic sheets (Garrity et al., 1992). However, though effective, most of these soil improvements are expensive and beyond the financial scope of farmers.

Reducing SP flows through reduced hydrostatic pressure can be achieved by changed water management. Instead of keeping the rice field continuously flooded with 5−10 cm of water, the floodwater depth can be decreased, the soil can be kept around saturation (SSC – saturated soil culture), or alternate wetting and drying (AWD) regimes can be imposed. In SSC and AWD, the duration of standing water in the field also decreases, which leads to reduced losses of water by evaporation. Under these management schemes, the hydrology of the soil changes from anaerobic under flooded and SSC regimes to alternately anaerobic and aerobic under AWD. Ultimately, rice may be grown under completely aerobic conditions and continuous SP and evaporation from standing water may be eliminated completely. Below, these water management technologies are reviewed in more detail.

2.1. Saturated soil culture (SSC)

In SSC, the soil is kept as close to saturation as possible. This mostly means that a shallow irrigation is given to obtain about 1-cm floodwater depth a day or so after the disappearance of standing water. From 1988 to 1997, Tabbal et al. (2002) experimented with the implementation of SSC in farmers' fields in Central Luzon, Philippines. They compared the yield and water use of the farmers' conventional practice of keeping the field continuously flooded with that of SSC (Table 1). The water inputs under the conventional practice ranged from 577 to 3,500 mm, depending on soil type and groundwater depth. With SSC, the water inputs decreased by 30−60% and the yield dropped by 4–9%, with one exceptional value of 30% in the very permeable soil of Guimba-2 in 1991. Because the water inputs decreased more than the yields, the water productivity (calculated as the ratio of yield over total water input) increased by 30−115%.

Bouman and Tuong (2001) compiled a database on SSC and AWD from their own IRRI experiments and experiments reported in the literature. Their database contains information from 31 pot and field experiments carried out in north-central India, the Philippines (Luzon), and Japan. In the 34 data points on SSC, water input decreased by 5% to 50% from the continuously flooded check, with an average of 23%. The yields decreased by only 6% on average, so that water productivity increased.

Implementing SSC requires good water control at the field level and frequent shallow irrigations that are labor-intensive. Borrell et al. (1997) experimented with raised beds in Australia to facilitate SSC practices. Water in the furrows (30-cm width and 15-cm depth) kept the beds (120 cm wide) at saturation. Compared to flooded rice, water savings were 34% and yield losses 16−34%. Thompson (1999) found that SSC in southern New South Wales, Australia, reduced both irrigation water input and yield by a bit more than 10%, thus maintaining the irrigation water productivity. A yield decline caused by cold damage is likely for current varieties grown using SSC in that

Table 1. Yield, water input, and water productivity under continuous standing water (CSW) and under saturated soil culture (SSC), Central Luzon, Philippines, 1988-97 dry seasons.

Location	Year	Crop establishment	Water inputs[a] (mm)		Yield (t ha^{-1})		Water productivity (g grain kg^{-1} water)	
			CSW	SSC	CSW	SSC	CSW	SSC
Guimba-1	1988	Transplanted	2,197	914	5.0	4.6	0.23	0.50
Guimba-1	1989	Transplanted	1,679	1,164	5.8	5.6	0.35	0.48
Guimba-2	1990	Transplanted	2,028	1,227	5.3	4.8	0.26	0.39
Guimba-2	1991	Transplanted	3,504	2,053	4.9	3.6	0.14	0.18
Muñoz	1991	Transplanted	694	373	7.4	6.7	1.06	1.81
Muñoz	1991	Wet-seeded	631	324	7.6	7.3	1.20	2.27
Talavera	1993	Transplanted	728	477	7.0	6.6	0.96	1.39
Talavera	1993	Wet-seeded	577	391	8.2	7.7	1.42	1.90
San Jose	1997	Wet-seeded	2,875	1,516	8.4	7.8	0.29	0.52

[a] Water inputs include rainfall and irrigation water applied during the crop growth period only. They do not include water inputs for land preparation.

environment. Borrell et al. (1997) pointed out the need for further research to determine which components of the water balance were responsible for the differences in total water use.

2.2. Alternate wetting and drying (AWD)

In AWD, irrigation water is applied to obtain 2–5-cm floodwater depth after a certain number of days (ranging from 2 to 7) have passed after the disappearance of ponded water. Though some researchers reported a yield increase under AWD (Wei and Song, 1989; Mao Zhi, 1993), our recent work indicates that this is the exception rather than the rule (Belder et al., 2002; Cabangon et al., 2001; Tabbal et al., 2002). In 92% of the 174 data points collected by Bouman and Tuong (2001), AWD resulted in decreased water input, though at the expense of 0–70% decreased yield compared with that of the flooded checks, depending on the number of days between irrigations and soil conditions (Fig. 1). Mostly, however, yield losses were smaller than the reductions in water inputs and water productivities increased with decreased water inputs (Fig. 2). Thus, there is a trade-off between land productivity (i.e., yield) and water productivity. In the most severe cases of AWD, water inputs decreased to only 300–400 mm and water productivities reached maximum levels of 2 g rice kg^{-1} water.

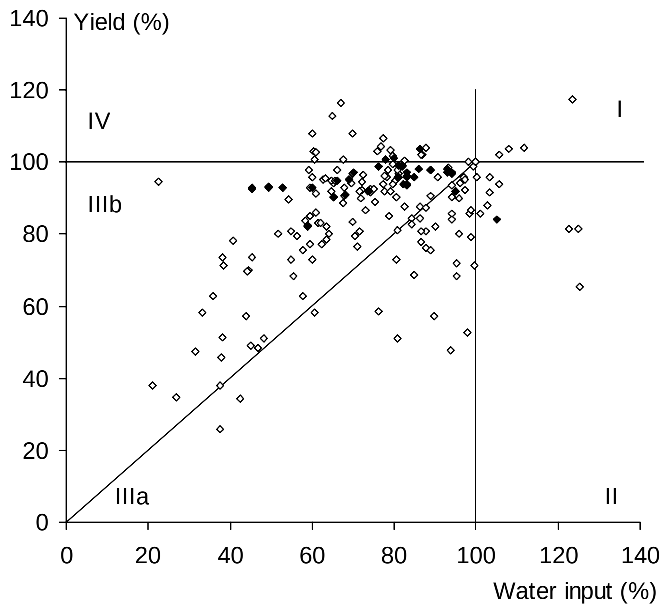


Fig. 1. Relative yield versus relative water input under saturated soil culture (SSC) (black diamonds) and alternate wetting and drying (AWD) (open diamonds) conditions. The relative yield and water inputs are calculated as the yield and water input of the SSC and AWD treatments as percentage of the yield and water input of the checks (continuous flooding), respectively. Data from Indian and Philippine field experiments. (Source: Bouman and Tuong, 2001.)

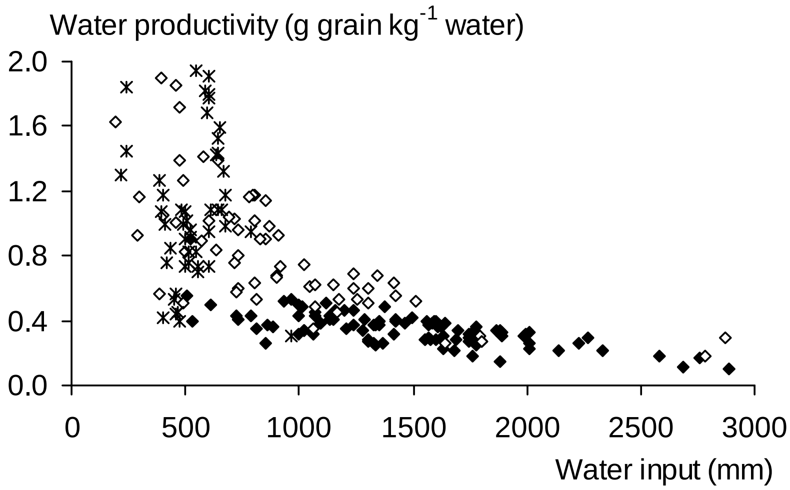


Fig. 2. Water productivity versus water input. ◆ are data from Indian field experiments (N = 99), ◇ are data from Philippine field experiments (N = 61), × are data from Japanese and Philippine pot experiments (N = 48). (Source: Bouman and Tuong, 2001.)

Fig. 3 shows so-called water production functions for two examples of AWD field experiments in India and closed-pot experiments in growth chambers in Japan. The lowest curved line is from Indian experiments in soils with SP rates of 21 mm d^{-1} and low nitrogen inputs of 80 kg N ha^{-1} and zero P and K (Jha et al., 1981). Yields were low and water consumption was high. On the right-hand side of the curve are the data of continuously flooded treatments. Going to the left are first AWD treatments that cut back SP while not affecting yield levels. Either the crop was able to satisfy its transpiration requirements or the low level of nutrients was more yield-limiting than water. Further to the left are data of more severe AWD treatments, and yields dropped when crop water consumption was negatively affected. The second, higher curve, is also from Indian experiments, but with lower SP rates (9–14 mm d^{-1}) and higher nutrient inputs (120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1}) that resulted in higher yields (Tripathi et al., 1986). Going from right to left on this curve, yields dropped faster than in the other experiment in India since water quickly became yield-limiting (compared with nutrients). Both Indian production curves illustrate the law of diminishing returns to water inputs. Water productivities are highest at the left side of the curves where water is the most limiting growth factor, but where yield levels are low. The data on the straight line are from closed-pot experiments in Japan (Anbumozhi et al., 1998). Since closed pots have no SP losses, reductions in water inputs immediately affected transpiration and, consequently, yields declined steeply with decreased water inputs.

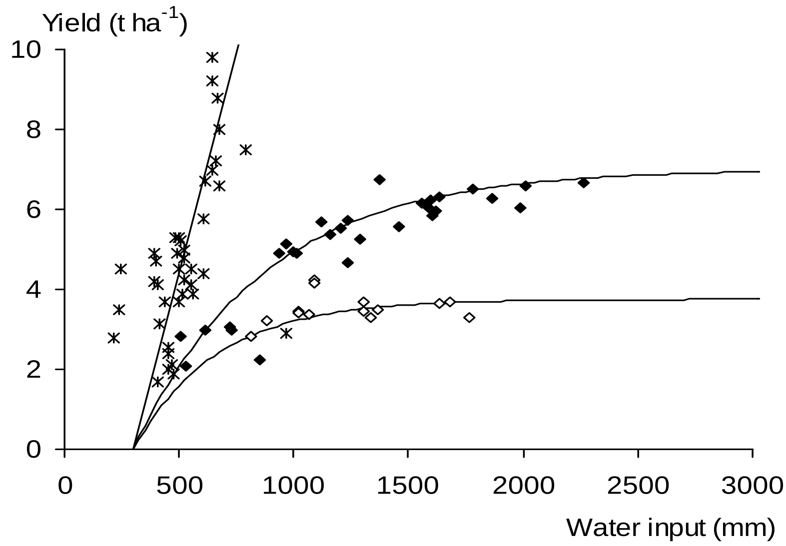


Fig. 3. Yield versus water input. Data from field experiments in India in 1976 and 1978 (◇, Jha et al 1981), in India in 1981-1982 (◆, Tripathi et al 1986), and in Japan (∗, Anbumozhi et al., 1998). The curved lines are fitted production functions of the shape [yield = $a*(1 - e^{(b*(\text{water input} - c))})$]. (Source: Bouman and Tuong, 2001).

2.3. Aerobic rice

A fundamental approach to reduce water inputs in rice is to grow the crop like an irrigated upland crop such as wheat or maize. Instead of trying to reduce water inputs in lowland paddy fields, the concept of having the field flooded or saturated is abandoned altogether. Upland crops are grown in nonpuddled aerobic soil without standing water. Irrigation is applied to bring the soil water content in the root zone up to field capacity after it has reached a certain lower threshold (e.g., halfway between field capacity and wilting point). The amount of irrigation water should match evaporation from the soil and transpiration by the crop. Since it is hardly possible to apply irrigation water to the root zone only, some of it is lost by deep percolation and is unavailable for uptake by the crop. Typical field application efficiencies vary from 60% to 70% using surface irrigation (e.g., flash or furrow irrigation) to more than 90% using sprinkler or drip irrigation.

The potential water savings when rice can be grown as an irrigated upland crop are large, especially on soils with high SP rates (Table 2). Besides cutting down on SP losses, evaporation also decreases since there is no continuous standing water layer. Traditional upland rice varieties are grown this way, but they have been selected to give stable yields in adverse environments with minimal external inputs. They are tall and unresponsive to inputs and, under favorable conditions, have a low harvest index (ratio of grain weight to total aboveground plant dry weight) and tend to lodge, or fall over (Lanceras et al., 2002). Alternatively, high-yielding lowland rice grown under aerobic conditions shows great potential to save water, but at a severe yield penalty. Achieving high yields under irrigated aerobic conditions requires new varieties of ‘aerobic rice’ with improved lodging resistance and the ability to partition a greater proportion of plant matter into grain.

Temperate aerobic rice. In the temperate zone, studies on lowland rice grown under aerobic conditions with sprinkler irrigation were conducted in the United States by McCauley (1990) and Westcott and Vines (1986). Irrigation water inputs were 20–50% less than under flooded conditions, depending on soil type, rainfall, and water

Table 2. Comparison of water use of a hypothetical aerobic rice crop with that of lowland rice on different soils types (characterized by different seepage and percolation rates).

Water flow process	Aerobic rice (mm)		Lowland rice (mm)		
Evaporation	100	100	200	200	200
Transpiration	400	400	400	400	400
Seepage and percolation	–	–	100 (1 mm d^{-1})	500 (5 mm d^{-1})	1,500 (15 mm d^{-1})
Application inefficiency loss	90 (85% eff.)	335 (60% eff.)	–	–	–
Total	590	835	700	1,100	2,100

management. The highest-yielding cultivars (7–8 t ha^{-1}) showed yield reductions of 20–30% compared with flooded conditions. The most drought-tolerant cultivars produced the same yields (5–6 t ha^{-1}) under both conditions. Researchers obtained similar results with rice grown under sprinkler irrigation in Australia (Blackwell et al., 1985). With high levels of irrigation, yields were 4–6 t ha^{-1} (compared with around 7 t ha^{-1} under flooded conditions) and water inputs were 20–50% of those under flooded conditions. Under the prevailing market structures in the U.S. and Australia, the 20–30% yield loss outweighed the benefits of the water savings, so research was discontinued. In Brazil, a breeding program on upland rice has resulted in improved varieties with a yield potential of up to 6 t ha^{-1} under sprinkler irrigation (da Silveira Pinheiro and da Maia de Castro, 2000). These new varieties possess the characteristics of modern plant types: medium stature and tillering, resistance to lodging, and short, erect upper leaves. Farmers grow these varieties commercially on an estimated 250,000 ha (Guimaraes and Stone 2000).

In all of the studies cited above – in the U.S., Australia, and Brazil – high yields are realized only when the soil is kept very wet (soil water tensions below 10–30 kPa) throughout the growing season. In northern China, as in Brazil, breeding efforts have produced temperate aerobic rice varieties (such as ‘Han Dao 297’, ‘Han Dao 277’, ‘Han Dao 502’, ‘Han Dao58’, ‘Danjing 5’, and ‘Danjing 8’) with a reported yield potential of up to 6 t ha^{-1} under supplementary irrigation (Wang Huaqi et al., 2002). These varieties have been released since the 1990s and it is estimated that they 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, and cotton) in low-lying flood-prone areas. The adoption of aerobic rice is facilitated by the availability of efficient herbicides and seed-coating technologies. Recent experiments near Beijing show that water savings of more than 50% can be realized compared with flooded lowland rice (Yang et al 2002). Importantly, yields of 4–5.5 t ha^{-1} are obtained using extremely little water (550–650 mm, versus 1,340 mm under lowland conditions; Table 3), resulting in much drier soil conditions (soil water tensions of 10–300 kPa) than in Brazil and in the studies in the U.S. and Australia. Another study in China comparing aerobic rice under various forms of ground cover with lowland rice confirmed the large potential for water savings (Lin Shan et al 2002).

Bouman et al. (2002) and Wang Huaqi et al. (2002) evaluated the performance of aerobic rice grown by farmers near Beijing and in a pilot site called Guanzhuang in Anhui Province in 2001 (Table 4). On average, the yield of aerobic rice was 27% to 35% lower than that of lowland rice and water inputs were 55% and 66% lower. Since the reduction in water use was relatively larger than the reduction in yield, the water

Table 3. Water inputs from emergence to harvest, yield, and water productivity of aerobic rice varieties HD297 and HD502 and lowland rice variety JD305 grown under flooded and aerobic conditions with different irrigation regimes near Beijing, 2001.

Growth condition	Water inputs (mm)	Yield ($t\ ha^{-1}$)			Water productivity (g grain kg^{-1} water)		
		JD305	HD297	HD502	JD305	HD297	HD502
Aerobic 1	644	4.2	4.7	5.3	0.65	0.73	0.82
Aerobic 2	577	3.8	4.3	4.6	0.66	0.74	0.80
Aerobic 3	586	2.0	4.2	4.3	0.34	0.72	0.73
Aerobic 4	519	1.5	3.4	3.5	0.29	0.66	0.67
Aerobic 5	469	1.2	2.5	3.0	0.26	0.53	0.64
Flooded	1,340	8.8	5.4	6.8	0.66	0.40	0.51

Table 4. Mean biophysical and socioeconomic performance indicators of aerobic rice and lowland rice produced by farmers at Guanzhuang (Anhui Province) and near Beijing, 2001.

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 grain kg^{-1} water)	0.95	0.58	0.96	0.51
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 d 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})	1.90	1.90	3.10	3.10

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

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

Source: Wang Huaqi et al., 2002.

productivity (g grain per kg of total water used) of aerobic rice was 1.6 to 1.9 times higher than that of lowland rice. 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 lowland rice. However, again because of aerobic rice's 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, 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 a water shortage (Guanzhuang) or government restrictions (Beijing).

Tropical aerobic rice. Although no effort has been made yet to breed rice varieties specifically for tropical aerobic rice systems, IRRI has identified several cultivars with high yield potential under aerobic management. Upland rice grown under favorable conditions typically reaches maximum yields of more than 4 t ha^{-1}, with yields of 5 t ha^{-1} and more sporadically reported (George et al., 2001, 2002). In the early 1970s, De Datta et al., (1973) tested lowland variety IR20 in aerobic soil under furrow irrigation at IRRI. Water savings were 55% compared with flooded conditions, but the yield fell from about 8 t ha^{-1} under flooded conditions to 3.4 t ha^{-1} under aerobic conditions. IRRI started to develop tropical aerobic rice systems in 2001, using existing improved upland and lowland germplasm (Castañeda et al., 2002). Using a promising new upland rice variety, Apo, dry-season yields at the IRRI farm in Los Baños, Philippines, reached a maximum of 5.7 t ha^{-1} in 2002 (Table 5). Though yields were on average 26% lower than under flooded conditions, water inputs were 44% lower and water productivities 35% higher. As in China, researchers identified specially bred aerobic rice varieties and proper management of water and nutrients as keys to obtaining high yields.

In India, researchers are currently testing the growing of popular lowland rice varieties under aerobic conditions on raised beds. The first results on yields and water use were comparable with those obtained at IRRI (Singh et al., 2002; Sharma et al., 2002). Important yield-reducing factors include weeds, micronutrient deficiencies, and nematodes. Keeping the soil flooded for the first few weeks of establishment is a

Table 5. Total water input (from land preparation to harvest), yield, and water productivity of rice variety Apo under flooded (F) and aerobic (A) soil conditions, IRRI farm, 2001-02.

Item	Dry season 2001		Wet season 2001		Dry season 2002	
	F	A	F	A	F	A
Water (mm)	1,672	744	1,759	959	1,275	852
Yield (t ha^{-1})	5.9	3.56	4.87	4.1	7.33	5.66
Water productivity (g grain kg^{-1} water)	0.35	0.48	0.28	0.43	0.57	0.66

suggested remedy for micronutrient deficiencies and weeds. Research on yield sustainability in aerobic systems has been limited in Asia. In Brazil, it is reported that high yields can be sustained when aerobic rice is grown once in four crops, but not under continuous monocropping (Guimaraes and Stone., 2000). A rapid yield decline under continuous upland rice cropping has also been documented in the Philippines (George et al., 2002). The decline, which cannot be reversed with inorganic fertilizers, may be related to the buildup of soil pathogens.

3. The technology transfer for water savings (TTWS) project

The TTWS project is the Philippines implementation of the international (Philippines, China and India) Water Workgroup of the Irrigated Rice Research Consortium (see IRRC page at the IRRI website www.cgiar.org/irri). The objectives of the workgroup are to:

1. Obtain insights in current water-saving practices by farmers and identify their behavior in coping with water scarcity;
2. Inventory water-saving technologies and identify the most promising ones; and,
3. Promote the spread and exchange of information on sustainable water-saving technologies that increase the productivity and value of water, optimize farmers objectives and maintain the water resource base.

In the Philippines, objective 1 was addressed so far through surveys executed among farmers in surface (gravity), deep-well and shallow tubewell irrigation schemes in Nueva Ecija and Tarlac. Objective 2 is addressed by literature reviews and by the organization of an international workshop called ‘Water-Wise in Rice Production’ at IRRI, April 2002. Objective 3 is the core of the TTWS project. Its specific purpose is to develop and implement a framework for transfer, adaptation and adoption of knowledge on water-saving technologies.

3.1. Project partners and the pilot sites

The project is truly a collaborative one involving a national rice research institution mandated to undertake rice research and development (PhilRice); the National Irrigation Administration that administers various water resource systems (NIA) and the International Rice Research Institute (IRRI). Considered as part of the project team are farmer-cooperators who are themselves members of Farmer Irrigator Associations or Cooperatives.

The project's study area is central Luzon (Fig. 4). An important (reservoir-backed) gravity irrigation system here is the Upper Pampanga River Integrated Irrigation System (UPRIIS), covering some 100,000 ha but scheduled to be increased to some 130,000 ha in the coming years. Beside UPRIIS, shallow tubewell and deepwell pumps owned and operated by farmers groups and individuals are commonly found in Bulacan, Pampanga, Tarlac and Nueva Ecija. For the initial implementation in the 2002 dry season, farmers getting irrigation water from deepwells and shallow tubewells were selected for two reasons. First, since these farmers directly face the costs of pumping water, they are considered most susceptible to use technologies that help save water and reduce costs. Second, it is easier to manage and control water in small-scale deepwell and private shallow tubewell systems than in large gravity irrigation systems such as UPRIIS. If the practice of water saving will be accepted by pump users, the next territory to conquer will be those covered by the gravity systems.

3.2. Technology selection: alternate wetting and drying

AWD was the first water saving technology promoted in the pilot sites in the Philippines. Table 6 shows the number of farmer-cooperators of alternate wetting and drying and aerobic rice from Tarlac and Nueva Ecija pilot sites. Alternate wetting and drying was carried out only during the dry seasons (DS 2002 and 2003), while aerobic rice was tested for the 2002 wet season and the 2003 dry season. A total of 21 farmers volunteered to participate in AWD during 2002 dry season, and about 26 farmers in the following 2003 dry season. The selection of farmers were based on motivation and willingness to participate in the field trials, and on site criteria like accessibility, spread of farmers across the site, position on the toposequence, and nearness to pump. A special effort was made to select farmers on different toposequence positions (high, middle, low elevation) to capture differences in groundwater status and soil type since these are expected to affect the actual number of days the crop can be without standing water.

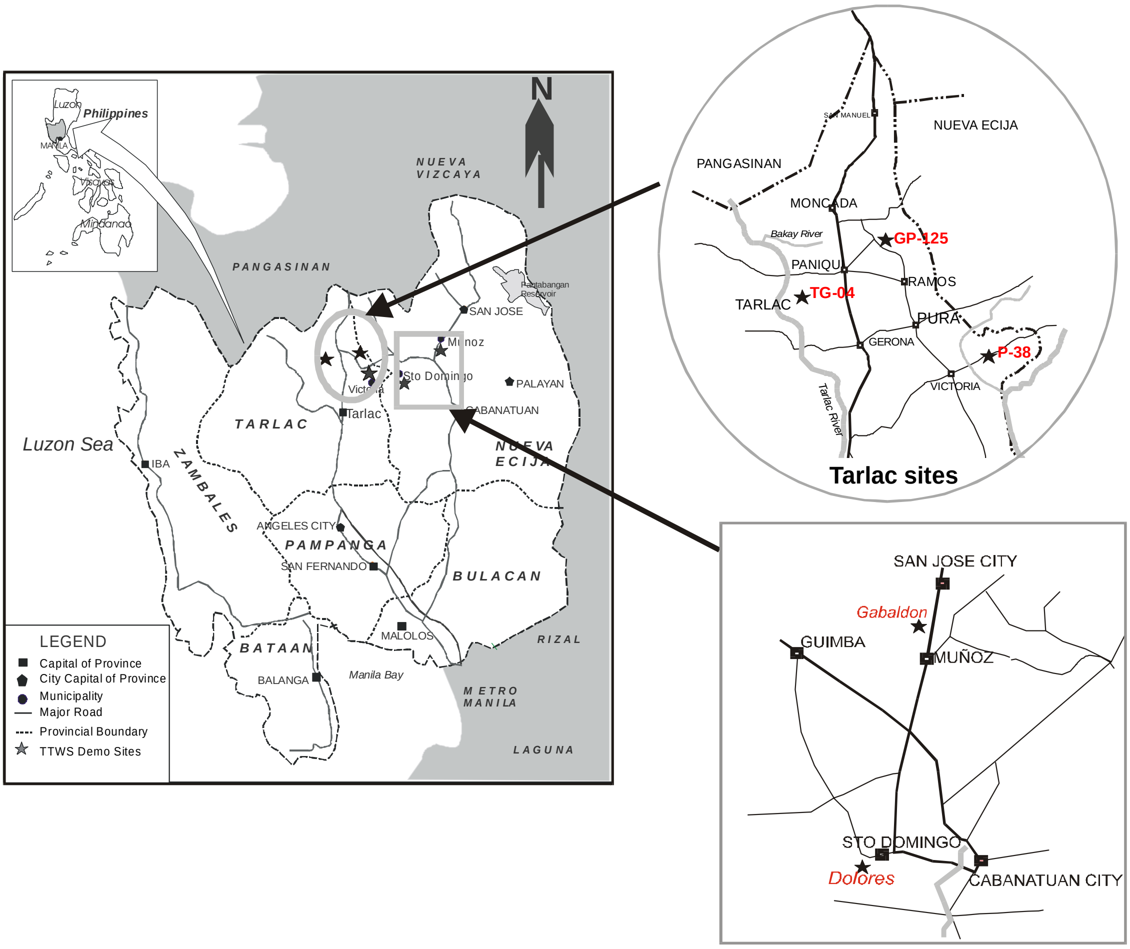


Fig. 4. Location of pilot sites (asterixes) in Central Luzon, Philippines.

Table 6. Number of farmer-cooperators in the TTWS project.

Location	Number of farmer-cooperators			
	AWD		Aerobic rice	
	2002 DS	2003 DS	2002 WS	2003 DS
A. Tarlac sites (deepwell)				
Canarem (P-38)	11	15	3	-
Dapdap (TG-04)	-	-	2	12
Pansi (GP-125)	-	-	1	8
B. Nueva Ecija sites (shallow tubewell)				
Dolores	5	5	2	5
Gabaldon	5	6	1	4
Total	21	26	9	29

Each farmer-cooperator participated with two fields: one managed using his standard farmer's practice (FP), and the other managed as alternate wetting and drying (AWD). Each field size was about 500–1000 m^2, with an internal farm ditch. Wetland preparation was done using the standard hand tractor driven disc plow, followed by two harrowings and one leveling for better water control and weed management. In Canarem and Gabaldon, crops were transplanted, spaced at 20 × 20 cm. Farmer-cooperators in Dolores established their crop by wet seeding. Production inputs were the same for both AWD and FP plots. Rice crops were transplanted between the last week of December to the middle of January for both 2002 and 2003 dry seasons in Canarem, while a much later crop establishment (from first to third week of January) was done for Dolores and Gabaldon sites because the farmer-cooperators were still busy planting onions and other upland crops during the middle to last week of December.

In the P-38 deepwell irrigation system in Canarem, water is distributed to the service area rotationally, where each farmer received irrigation water once a week, and usually maintained 6 to 8 cm of ponded water after irrigation. Irrigation schedules for AWD and FP plots followed the rotational irrigation schedule of the sectors. However, to differentiate the water management of the AWD and FP plots, the amount of irrigation water supplied at the AWD plots was made to be about 30 to 40% lower than that supplied to the FP plots at each irrigation. In the shallow tubewell systems in Nueva Ecija, FP plots were almost continuously flooded, while irrigation in the AWD plots was done only after 4 to 5 days of no standing water in the field. Irrigation water was measured using trapezoidal weirs. Staff gages were also installed to measure daily ponded water depth in the plots.

Perched water table and groundwater levels in the AWD and FP plots were monitored using PVC tubes. Divers (groundwater level data loggers) were also installed in the pilot sites to continuously monitor groundwater level fluctuations. Rainfall and evaporation data in Canarem were obtained from the agro-meteorological station installed in the area, which consists of Class A evaporation pan and true-check rain gage. Rainfall and evaporation for the Nueva Ecija sites were taken from the agro-meteorological station in PhilRice, Muñoz. Calendar-type monitoring sheets were given to the farmer-cooperators in all pilot sites to record all their field operations, labor used, and all inputs applied in the AWD and FP plots. Yields were taken from crop-cut samples collected from two 2 × 2.5 m^2 sampling area in the FP and AWD plots. The actual yields from the whole plots were also taken for comparison.

3.3. Tropical aerobic rice participatory R&D

Initially nine farmer-cooperators were identified and selected during the 2002 wet season (WS) in Tarlac and Nueva Ecija to participate in the first exploratory trials of aerobic rice under farmer field conditions. In the 2003 dry season (DS), the number of farmer-cooperators was increased to 29. The farmer-cooperators were selected based on representativeness of their fields and their willingness to participate in the R & D process.

For both seasons, each farmer-cooperator was requested to test one of the three promising aerobic varieties (APO, UPLRI-5 and Magat). Farmers who volunteered or selected to test these varieties were either at the edge of the pump area or situated on the higher sites, with relatively large water losses and dry soil conditions. Fields were prepared dry using either animal or tractor, and rice seeds were dry seeded (in rows) in relatively dry soil with a seeding rate of about 80 to 100 kg ha^{-1}. In the 2002 WS, the establishment was done using a *lithao*, a wooden implement to open the furrows (low tech); the seeds were hand-sown; and basal fertilizer was broadcast. However, in the 2003 DS, a mechanical seeder (high tech) was also used in seed establishment, which is pulled by big tractor for direct seeding and direct placement of basal fertilizer. Most of the farmer-participants tried both the low technology (low tech) and the high technology (high tech) level of seed establishment by either contributing two plots, or splitting one big plot into two sub-plots. Both ‘low tech’ and ‘high tech’ areas were laser-leveled before seeding. For uniformity in the technology adaptation, cultural management practices and inputs such as rice seeds, fertilizers and chemicals calculated for the area of the participating fields, as well as technical support were provided by the project. The farmers provided the day-to-day management of the fields, as well as the labor and power for land preparation, crop establishment, weeding, spraying, harvesting and threshing. Supplementary irrigation was given to the crop for crop growth, although the amount of water was not measured.

Farmers were asked to conscientiously record all their operations such as labor and other inputs (seeds, fertilizer, pesticides, etc.) in the forms provided. Long tubes were installed to monitor daily groundwater table at each farmer’s field. Emergence, flowering and harvesting dates were recorded. For the estimate of grain yields, two sources of data were utilized: (1) crop cut samples were obtained from two 10-m^2 sampling spots, and (2) the yield of the whole field per record of the farmers obtained during the interview. The cut crop samples were threshed, sun-dried, and weighed and the moisture content determined. Other observations such as pest and disease occurrence, rodent infestation, lodging, weed pressures, etc. was noted.

4. Results and discussions

4.1. Alternate wetting and drying

Perched water table and groundwater level fluctuation. In Canarem, perched water table and groundwater level dynamics in both AWD and FP plots were affected by the timing of irrigation delivery and toposequence positions. Periodic water table rise in AWD and FP plots during 2002 DS was caused by the irrigation water applications (Fig. 5). However, the degree of fluctuations vary across the toposequence positions. The seasonal average perched water table depth of plots located in the high positions was about 40 cm lower than in the low positions. The shallow water table in the low areas was attributed to the collected seepage from the high and middle portions of the service area. To compare AWD and FP plots, perched water table and groundwater table depths in AWD plots were relatively deeper (but not significantly different) than in FP plots caused by higher initial ponding depths of the latter. However, in the low toposequence, no noticeable differences in depths between AWD and FP plots were observed and both had water tables that were already very close to the ground surface.

Groundwater depths in Gabaldon were deeper than in Canarem and Dolores, and were more than 3 m below the ground surface during the entire growing season. Previous studies by Igbokwe (1992) showed that during dry season in Gabaldon, the deepest groundwater depth was recorded at 8.4 m below the ground surface and in the dry season the average depth was 7.4 m. During the peak season of crop growth (February-March), some farmers had to lower their pumps to draw groundwater. Perched water table dynamics were shallower, only fluctuated from 0 to 60 cm below the ground surface (Fig. 6). On the average, FP plots had a shallower perched water table depth than AWD plots.

Perched water table depths in Dolores were shallower (but not significantly different) than in Gabaldon, ranging from 0 to 50 cm below the ground surface throughout the dry season (Fig. 7). In both FP and AWD plots, perched water table depths did not drop below the root zone (30-40 cm depth) throughout the season.

Based on the above results, the difference of the average perched water table depths between AWD and FP in all sites in Tarlac and Nueva Ecija were not really significant which showed that the farmers who were drawing water from deepwells and shallow tubewells were already practicing alternate wetting and drying at a certain extent, and their current water management practices only require minor refinement to optimize the benefits of alternate wetting and drying.

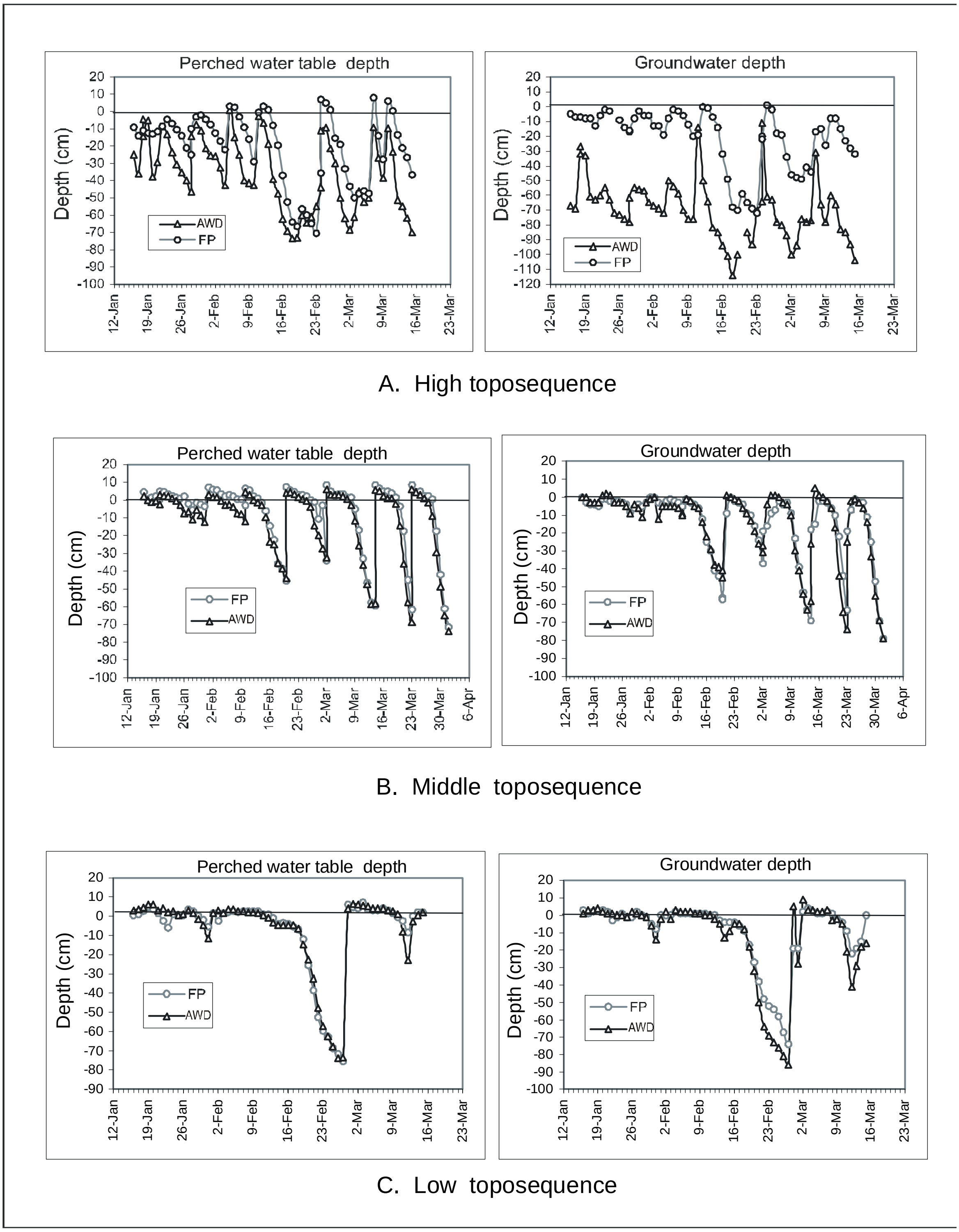


Fig. 5. Typical perched water table and groundwater depths at three toposequence positions in Canarem during 2002 dry season.

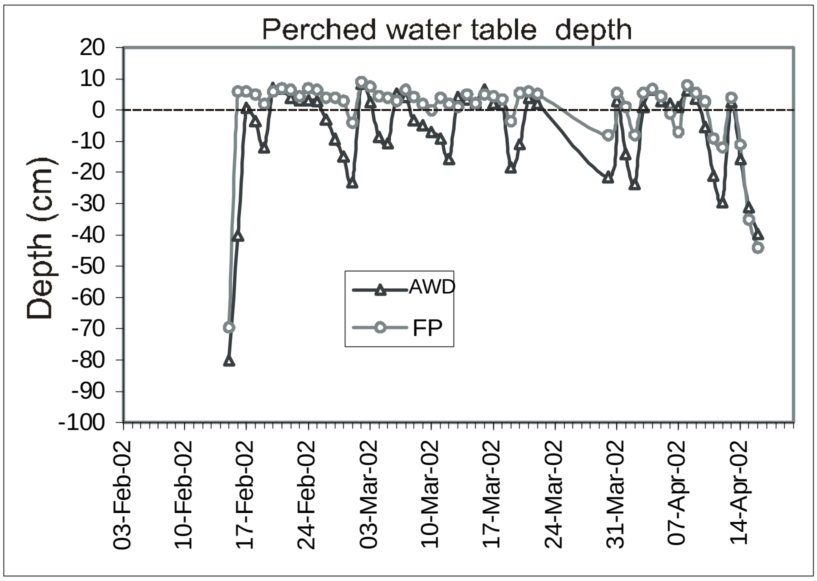
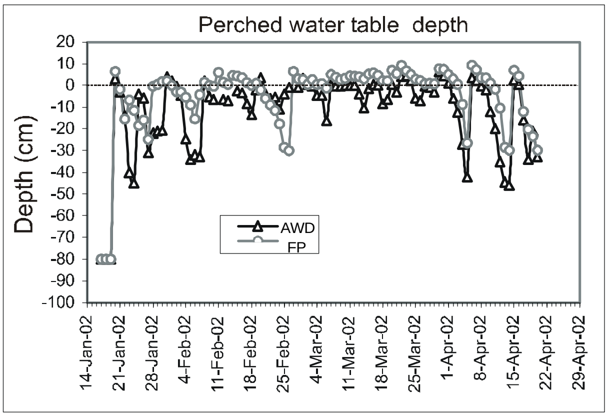


Fig. 6. Typical perched water table depth in Gabaldon in dry season 2002.



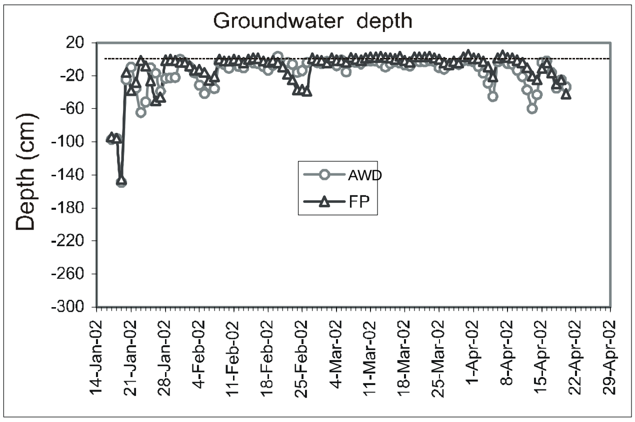


Fig.7. Typical perched water table (left) and groundwater (right) depths in Dolores in 2002 dry season.

Irrigation water use. Farmers recognized that AWD saves water. In Canarem, mean total water use was highest in high elevations in both AWD and FP plots in both years (Fig. 8). This was attributed to its lighter soil texture (fine silty loam) and lateral seepage towards the lower toposequence positions. During its first season of implementation (dry season 2002), the difference in total water use between AWD and FP plots was also highest in high elevations (24%), compared to 20% and 5% in middle and low toposequences, respectively. The following year, farmers became more confident on AWD and as a result a much higher savings was achieved especially in high elevation (33%). The average savings for all elevations was about 16% in 2002 and 24% in 2003.

In Gabaldon, the average percent difference in water used between AWD and FP practices was relatively low (11%) in 2002 DS (Fig. 8). In fact, three out of five farmer-cooperators had only savings of 2 to 8%, while only one farmer was able to achieve a saving of 31%. The small difference can be explained by the difficulty of water pumping due to the lowering of groundwater table. Consequently, these farmers decided to irrigate their FP plots almost like AWD plots. In Dolores, AWD plots used about 727 mm while the FP plots used 853 mm in 2002 DS, and the difference of 15% water used was not significant. A similar trend of water use was also observed in 2003 DS under the shallow tubewell systems (Fig. 8). On average, the number of irrigations was slightly higher in Dolores than in Gabaldon for both AWD (13.2 vs 12.6) and FP (14 vs 15.8) plots for the average of both seasons, respectively. Farmers in Dolores established their crops through direct wet seeding while the Gabaldon farmers transplanted their crops. As a consequence, extra irrigations were needed in Dolores to grow the seed to the seedling stage in direct-seeded rice crop establishment.

In general, the higher savings in 2003 (Fig. 8) reflect the effect of the learning process: at this time, farmers were already confident about the performance of AWD and willing to take more risk in saving more water. Farmers in Canarem (P38) said that, once the technology is adopted, more water will be saved, more rice farms can be irrigated, and more houses can be supplied with water now available for domestic use. In P-38, some 73% of the respondents said that irrigation water delivery to ISC

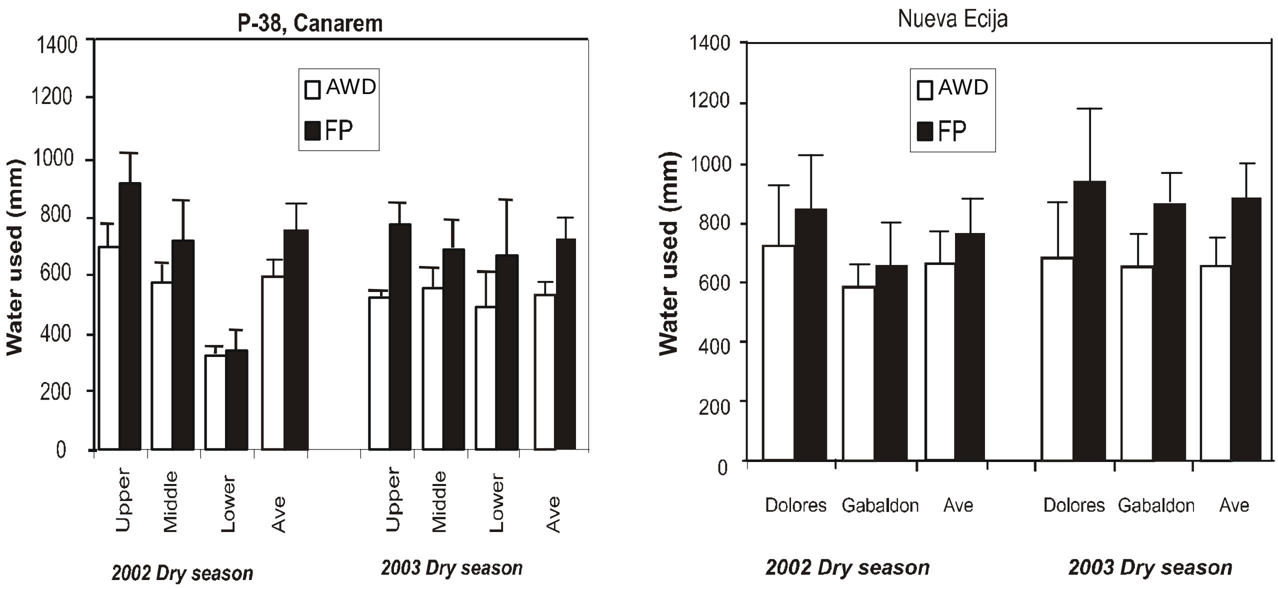


Fig. 8. Total water used (mm) at AWD and FP plots in Tarlac (left) and Nueva Ecija (right) for 2002 and 2003 dry seasons.

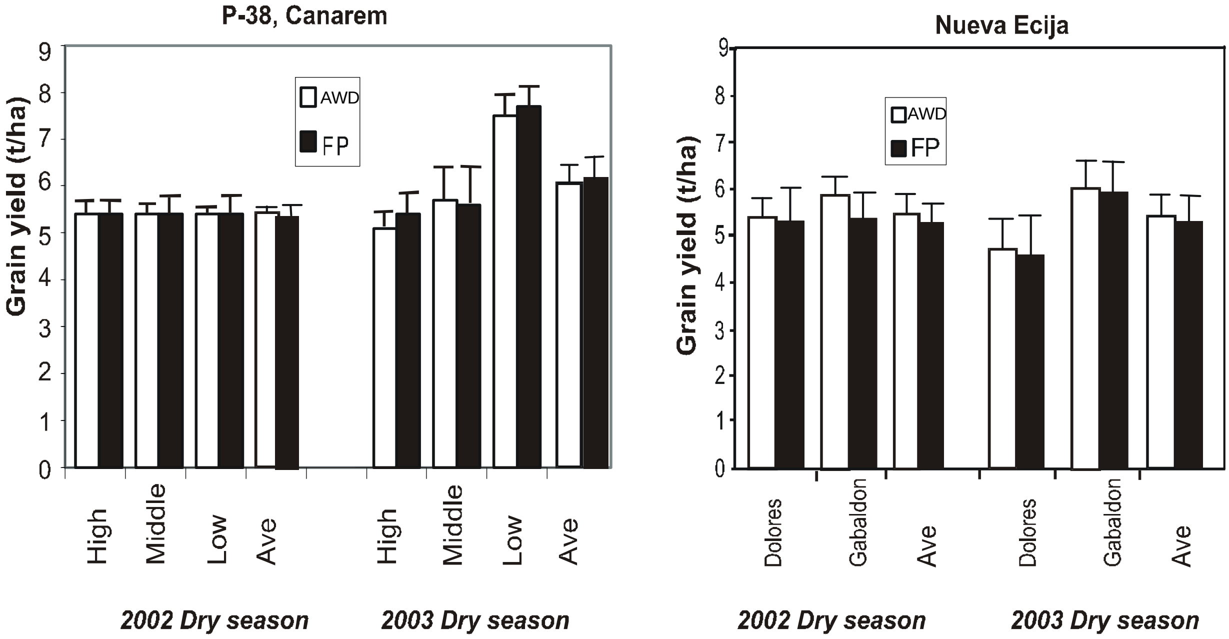


Fig. 9. Average yield in AWD and FP plots at the pilot sites in Tarlac (left) and Nueva Ecija (right) for 2002 and 2003 dry seasons.

member farmers could be substantially improved with respect to timeliness, reliability, and equity of water distribution if all members of the ISC would adopt AWD.

Grain yield. Farmers generally perceived that the yield in the FP plots was similar to that in the AWD plots, regardless of less water being used. This perception agrees with the yields obtained from the crop cut samples in Fig. 9.

In Canarem, the average grain yields did not vary significantly between AWD and FP plots for the two dry seasons. In the 2002 dry season, yields did not also vary across toposequence and ranged from 5.3 to 5.5 t ha^{-1}, with middle plots getting slightly higher yields. In DS 2003, the lower elevation plots got the highest average yield of about 7.5 t ha^{-1}, and was the only group that had a significant increase in yield between seasons. This was maybe because of various reasons such as better hydrology in the lower areas, and farmers used more fertilizers in the 2003 dry season. The mean yield of 4.6 t ha^{-1} of the all 63 members in 2003 was much lower than the 6.2 t ha^{-1} (FP) and 6.1 t ha^{-1} of our farmer cooperators. This is quite common phenomenon, reflecting the fact that usually farmers who are willing to try out new technologies and participate in research are farmers who are among the best producing farmers in the area. Moerover, their cooperation in the project increased their farming skills.

In Gabaldon, the yield differences between AWD and FP plots were also not significantly different in the two dry seasons, although AWD average yields are slightly higher than in FP plots in both years. There was also no significant difference of yields between the cropping seasons (Fig. 9). Average yields of AWD and FP plots in the wet-seeded rice in Dolores were about one ton lower than in Gabaldon during the 2003 DS (4.6 vs 5.8 t ha^{-1}), however, no significant yield difference was observed between the AWD and FP plots in both years.

Water productivity. Water productivity is computed as the grain yield in kilograms divided by the mean total irrigation plus rainfall in cubic meters. In Canarem, the average water productivity in the AWD plots was higher than in the FP plots at all three toposequence positions (Fig. 10). Plots at low toposequence had the highest productivity values of 1.7 and 1.6 kg m^{-3} in the 2002 dry season and 1.9 and 1.6 kg m^{-3} in the 2003 dry season for AWD and FP plots, respectively. Since yields were the same, the relatively high water productivity in low toposequence was caused by the lower water inputs. In Gabaldon and Dolores, water productivity in the AWD plots was higher than in the FP plots, but the difference was not statistically significant.

Cost and returns All farmer cooperators acknowledged that AWD saves time, labor and expenses. It reduced costs by using 20-25% less fuel and oil as shown in Table 7. It reduced labor as farmers spent less number of hours in irrigation (depending on the distance).

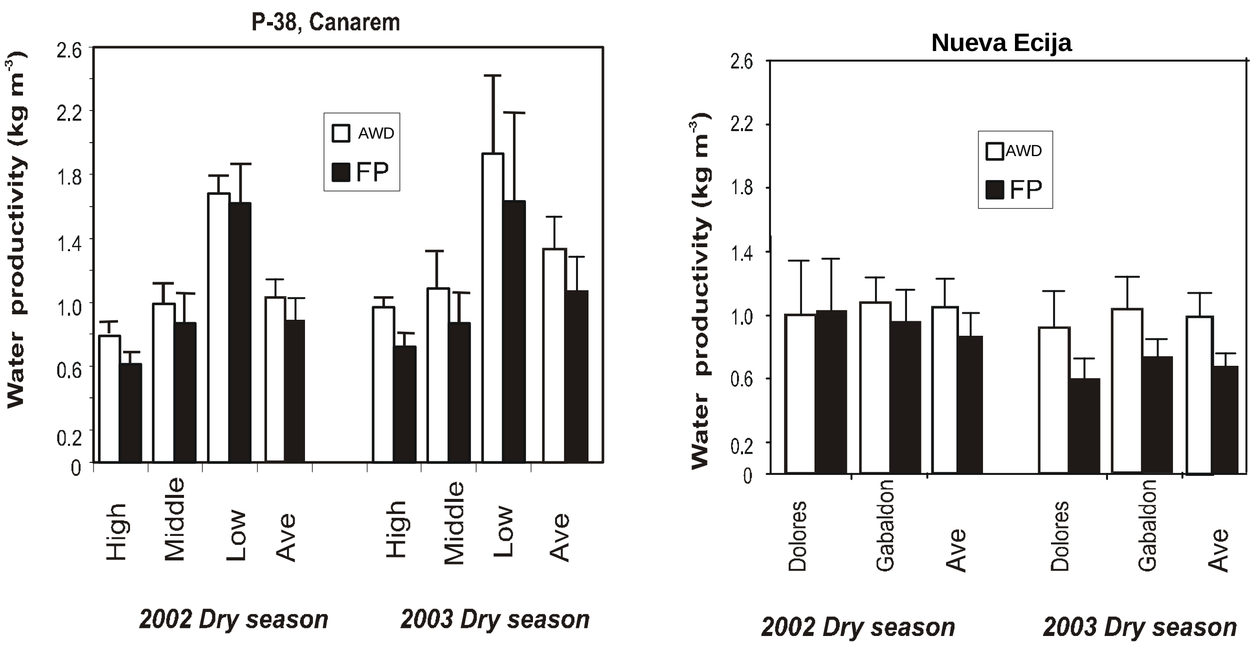


Fig. 10. Average water productivity (kg m^{-3}) at the pilot sites in Tarlac (left) and Nueva Ecija (right) for 2002 and 2003 DS.

Table 7. Average yields, cost and returns of rice crop grown under two water management practices for 2002 and 2003 DS.

ITEM	Canarem (Deepwell)		Gabaldon* (Shallow tubewells)		Dolores* (Shallow tubewells)	
	FP	AWD	FP	AWD	FP	AWD
2002 dry season						
Gross return (US\$ ha^{-1})	932.7	932.7	1182.6	1291.6	1073.5	1042.9
Total Production cost (US\$ ha^{-1})	441.2	397.3	897.6	851.4	599.3	598.6
Net profit (US\$ ha^{-1})	491.5	535.5	297.0	425.0	474.2	444.35
Net profit-cost ratio	1.14	1.37	0.46	0.55	0.34	0.35
2003 dry season						
Gross return (US$/ha)	1133.6	1105.2	N/A	N/A	N/A	N/A
Total Production cost (US\$ ha^{-1})	519.0	491.3	N/A	N/A	N/A	N/A
Net profit (US\$ ha^{-1})	614.6	613.9	N/A	N/A	N/A	N/A
Net profit-cost ratio	1.18	1.25	N/A	N/A	N/A	N/A

* N/A: data are still not available (analysis in progress for 2003 DS).

On average, there was no significant difference of the gross returns between FP and AWD plots in Canarem for the two years of dry season cropping. During the first dry season implementation of the project, the average total production cost per hectare under FP was higher than AWD (441 versus 397 US$) which was attributed to higher fuel and oil consumption in FP plots. As a result, the 2002 dry season net profit in AWD was slightly higher than in FP plots by almost US\$45 ha^{-1}. However, during the next dry season (2003), the disparity of the amount and cost of irrigation had reduced which resulted in almost the same net profits of AWD and FP. This was probably because the farmers gained more confidence on AWD during the past dry season and they tried to copy the irrigation scheme of AWD to their FP plots. The average 2-year net profit-cost ratio was slightly higher in AWD plots (1.31) than in FP plots (1.16), which showed the slight economic advantage of AWD over FP.

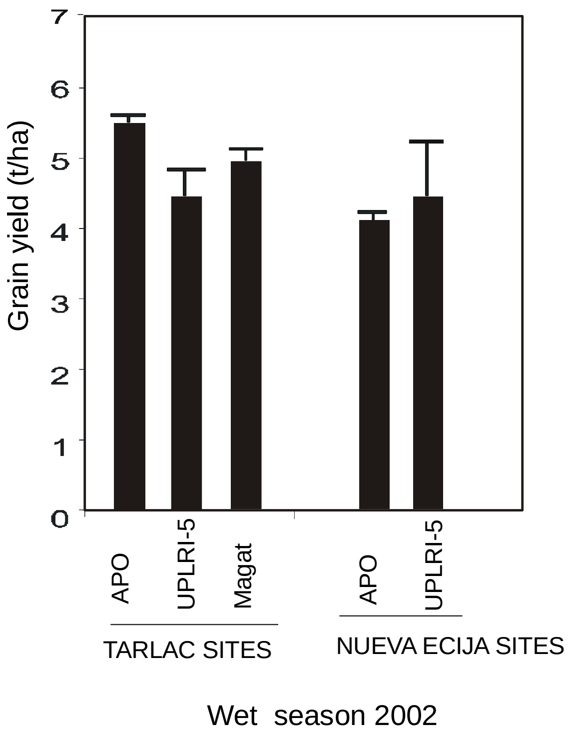
In Gabaldon, only data from the 2002 DS is presented in this paper. The average total gross return under AWD was higher than under FP by about US$110 (Table 7). However, the total production cost was lower in AWD than in FP by about US$46, which was attributed to lower pumping cost (fuel and oil) and fertilizer cost. Total number of irrigations in AWD plots was less than in FP plots (12.6 vs 14 irrigations). Due to higher total gross returns and lower total production costs, the difference of the net profit per ha between AWD and FP was about US$127.

In Dolores, total gross return was slightly higher in FP plots than in AWD plots, although the difference was not significant. Also, total production costs were not significantly different between the two water management practices (Table 7). On average, net profits obtained in Dolores for the AWD and FP plots were higher than in Gabaldon because of the lower cost of crop establishment (direct seeding) in Dolores. Moreover, the groundwater table in Dolores was shallower and the farmer-cooperators' fields were located in a contiguous area, where one field can receive seepage water from the neighboring fields that resulted to lower pumping cost.

4.2. Aerobic rice

About 1500 mm of rain fell in Tarlac and Nueva Ecija sites from seeding to harvest during the 2002 WS, of which more than 50% occurred from the last week of June to middle of July. However, in 2003 DS, almost no rainfall was recorded in the pilot sites.

During the 2002 WS in Tarlac, Apo yielded the highest among the three varieties with an average yield of 5.5 t ha^{-1}, while Magat and UPLRI-5 yielded 5.0 and 4.5 t ha^{-1}, respectively (Fig. 11). In the Nueva Ecija sites, Apo yielded an average of 4.1 t ha^{-1}, while the UPLRI-5 yielded about 4.5 t ha^{-1}. The low yield of Apo in Nueva Ecija



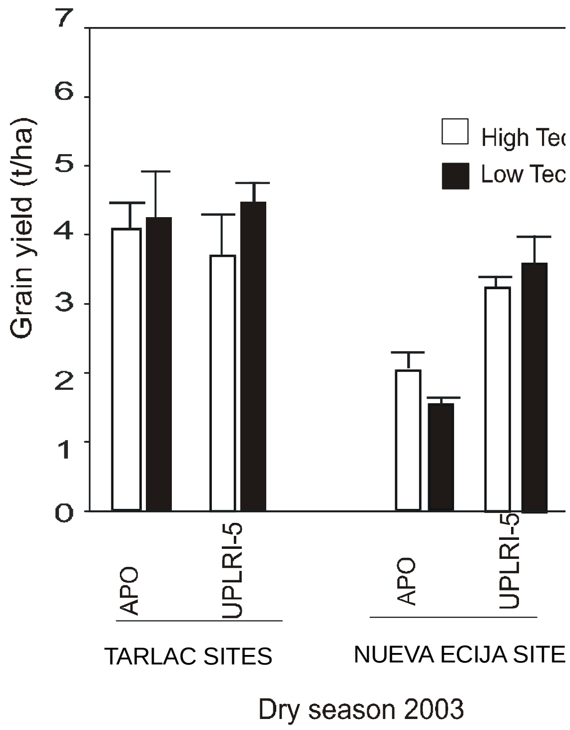


Fig.11. Average grain yields (t ha^{-1}) of aerobic rice varieties in Tarlac and Nueva Ecija sites during 2002 WS and 2003 DS.

site was caused by severe lodging during the flowering stage. Unfortunately, the number of sample farmers was only 9, compared to 29 farmers during the 2003 DS, and results may be inconclusive due to the limited samples if we try to compare the aerobic rice results with the farmers' varieties.

Nonetheless, the yield advantage during the 2002 DS of the three aerobic rice varieties in Dapdap (GP-04) was evaluated by comparing them with the yields sampled from the 25 neighboring farmers' fields in the area. Most of these farmers grew rice by dry seeding in hills along the rows using different lowland varieties.]yields at neighbouring fields in Dapdap ranged from 2.1 to 4.8 t ha^{-1} with an average of 4 t ha^{-1}, which was about 1.5 and 1.3 t ha^{-1} lower than the average yield of Apo and Magat, respectively. However, UPLRI-5 yield was not significantly different from the average yield of neighboring farmers.

With more farmer-cooperators participated in the development of the aerobic rice technology during the 2003 dry season, a wide range of yield results was observed. The yield range for all varieties in 2002 was 4–5 t ha^{-1}, while in 2003, the yield was 2-6.6 t ha^{-1}. In terms of varietal performance, Apo was better than UPLRI-5 in Tarlac for 2003 DS. The average yields were 4.0 and 3.4 t ha^{-1} from the crop cut estimate. The differences in yields between the two varieties, however, were not significant using the paired t-test. The crop establishment technology imposed on aerobic rice did not have a consistent and significant effect on the yield performance. The crop cut estimates at the low-tech level had relatively higher values compared to the high-tech level for the two varieties, however, the differences were not significant. It was difficult to establish the relationship of yield and seeding dates because the range of the seeding date was limited (aerobic rice was established from December 5 to December 20 only).

5. Summary and conclusions

Water in irrigated rice production has been taken for granted for centuries, but the 'looming water crisis' may change the way rice is produced in the future. Water-saving irrigation technologies that were investigated in the early 1970s, such as saturated soil culture and alternate wetting and drying, are receiving renewed attention by researchers. These technologies reduce water inputs, though mostly at the expense of some yield loss. Farmers in Asia that are confronted with scarcity or high costs of water have already started to adopt these technologies. In China, various forms of alternate wetting and drying and reduced floodwater depth have been developed and massively adopted by farmers (Li, 2001). Surveys in north-central India (A.K. Singh, personal communication) and in Central Luzon (unpublished IRRI data) show that farmers that operate pumps to irrigate their paddy fields consciously apply some form of alternate wetting and drying to save energy costs.

Aerobic rice is a new concept to further decrease water requirements in rice production. It is commercially grown in Brazil and is being pioneered by farmers in northern China. In the heart of the rice-wheat belt in India (Haryana, the Punjab, and Uttar Pradesh), innovative farmers are pioneering growing rice aerobically under furrow irrigation in raised-bed systems (Ladha et al., 2000). Changes in the hydrology of rice production will have major consequences for its sustainability and appropriate management practices. Over the centuries, lowland rice has proven to be a remarkably sustainable system, mostly because of its particular anaerobic character. Water-saving irrigation practices shift away from continuous anaerobic conditions to alternate anaerobic-aerobic and continuous aerobic conditions. The shift from anaerobic to aerobic systems will have major consequences for weed, pest, and disease ecology, nutrient and soil organic matter dynamics, and greenhouse gas emissions and carbon sequestration. Weed control is especially a crucial issue in most water-saving irrigation technologies. Water has been the cheapest herbicide ever, but this may not be so anymore in the (near) future. Breeders have to respond to the challenge of breeding varieties that perform well under nonpermanently flooded conditions. The development of aerobic rice varieties is probably the most ambitious challenge of all.

The results of the AWD trial in Canarem, Gabaldon and Dolores have provided a good indication that alternate wetting and drying is a viable alternative in improving water productivity in both deepwell and shallow tubewell irrigation systems. A significant water saving of about 20% was attained in deepwell systems and about 11-15% in shallow tubewells,although it could go up to 40% as demonstrated by some farmers. In terms of yield penalty, there was no significant reduction in yield between AWD and FP plots. In Canarem, for two dry seasons, AWD plots obtained higher profit of US\$ 575 ha^{-1} as against US\$ 553 ha^{-1} in FP plots. In Gabaldon, a net profit per ha of US\$ 425 was attained in the AWD and US\$297 in the FP plots, while in Dolores, the net profit per ha in AWD plots was slightly lower (US\$ 444) compared to FP plots (US\$ 474).

The two-season trials of the promising ‘aerobic’ rice varieties in Tarlac and Nueva Ecija sites showed remarkable yield performance. Higher yields were attained compared to the conventional lowland varieties where soils were very light, and farmers were practicing dry seeding for decades. A yield level of about 6 t ha^{-1} is achievable under farmer field conditions for both wet and dry seasons. Although farmers were very enthusiastic about adopting these varieties, there are still various issues that need to be understood and researched before a full-scale dissemination of this technology can take place. Many problems were experienced in the aerobic rice system especially during the dry season trials, including water stress, weed pressure, possible yield reduction due to continuous monoculture (nematode), nutrient management and others. These problems still need to be researched before moving to a wide scale diffusion of the technology.

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