Available online at www.sciencedirect.com
SCIENCE DIRECT®
Field Crops Research 96 (2006) 252–259
Field Crops Research
www.elsevier.com/locate/fcr

Comparison between aerobic and flooded rice in the tropics: Agronomic performance in an eight-season experiment

Shaobing Peng [a,*], Bas Bouman [a], Romeo M. Visperas [a], Ambrocio Castañeda [a], Lixiao Nie [b], Hong-Kyu Park [c]

[a] Crop, Soil and Water Sciences Division, International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines
[b] Crop Physiology and Production Center, Huazhong Agricultural University, Wuhan, Hubei 430070, China
[c] Honam Agricultural Research Institute, National Institute of Crop Science, Rural Development Administration, Iksan, Chonbuk 570-080, Republic of Korea

Received 10 April 2005; received in revised form 5 July 2005; accepted 6 July 2005

Abstract

Yield penalty and yield stability of aerobic rice have to be considered before promoting this water-saving technology in the tropics. The objectives of this study were (1) to compare crop performance between aerobic and flooded rice continuously over several seasons, and (2) to identify yield attributes responsible for the yield gap between aerobic and flooded rice. Field experiments were conducted at the International Rice Research Institute farm in dry and wet seasons. Grain yield and its components were compared between aerobic and flooded rice continuously for eight seasons from 2001 to 2004 using the best available aerobic rice varieties in the tropics. The yield difference between aerobic and flooded rice ranged from 8 to 69% depending on the number of seasons that aerobic rice has been continuously grown, dry and wet seasons, and varieties. When the first-season aerobic rice was compared with flooded rice, the yield difference was 8–21%. The yield difference between aerobic and flooded rice was attributed more to difference in biomass production than to harvest index. Among the yield components, sink size (spikelets per m^2) contributed more to the yield gap between aerobic and flooded rice than grain filling percentage and 1000-grain weight. Yield decline was observed when aerobic rice was continuously grown and the decline was greater in the dry season than in the wet season. The yield decline of aerobic rice was attributed more to changes in biomass production than in harvest index. Our data suggest that new aerobic rice varieties with minimum yield gap compared with flooded rice and crop management strategies that can reverse the yield decline of continuous aerobic rice have to be developed before aerobic rice technology can be adopted in large areas in the tropics.

Keywords: Aerobic rice; Biomass production; Flooded rice; Grain yield; Yield decline

Rice production consumes about 30% of all freshwater used worldwide. Flood-irrigated rice uses two to three times more water than other cereal crops such as wheat and maize. In Asia, flood-irrigated rice consumes more than 45% of total freshwater used (Barker et al., 1999). However, scarcity of freshwater resource has threatened the production of the flood-irrigated rice crop (IWMI, 2000). By 2025, 15 out of 75 million hectare of Asia's flood-irrigated rice crop will experience water shortage (Tuong and Bouman, 2003).

Several technologies have been developed to reduce water loss and increase the water productivity of the rice crop. They are saturated soil culture (Borell et al., 1997), alternate wetting and drying (Li, 2001; Tabbal et al., 2002), ground cover systems (Lin et al., 2002) and system of rice intensification (Stoop et al., 2002). However, the fields are still kept flooded for some periods in most of these systems, so water losses remain high. Aerobic rice is high yielding rice grown under non-flooded conditions in non-puddled and unsaturated (aerobic) soil. It is responsive to high inputs, can be rainfed or irrigated, and tolerates (occasional) flooding (Bouman and Tuong, 2001). In this paper, aerobic rice refers to rice crop grown in non-flooded and non-puddled lowland soil with supplemental irrigation. Aerobic rice promises substantial water savings by minimizing seepage and percolation and greatly reducing evaporation (Bouman et al., 2002).

* Corresponding author. Tel.: +63 2 845 0563; fax: +63 2 891 1292.
E-mail address: s.peng@cgiar.org (S. Peng).

0378-4290/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2005.07.007

Experimentally growing high-yielding lowland rice varieties under aerobic conditions has shown great potential to save water, but with severe yield penalty. In the early 1970s, De Datta et al. (1973) tested the lowland variety IR20 in aerobic soil under furrow irrigation at IRRI. Water saving was 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. There was limited information on the difference in crop performance between aerobic and flooded conditions when varieties that are adapted to aerobic conditions were used. Furthermore, physiological basis of yield gap between aerobic and flooded rice has not been studied extensively. Such information is vital for identifying the physiological and morphological traits to support the selection and breeding of high-yielding aerobic rice varieties.

In Brazil, it was reported that high yields could be sustained when aerobic rice is grown once in four crops, but not under continuous monocropping (Guimaraes and Stone, 2000). Rapid yield decline under continuous upland rice cropping has been documented in the Philippines (Ventura and Watanabe, 1978). Yield decline under monocropping of aerobic rice has also been reported by George et al. (2002). The causes of yield decline in the continuous aerobic rice system remain unclear. The buildup of soil-borne pathogens such as nematodes is a likely candidate (Ventura et al., 1981). Understanding the causes of yield decline and physiological processes responsible for the yield gap between aerobic and flood-irrigated rice will be useful for developing crop and resource management strategies to improve the grain yield and yield stability of aerobic rice. Because of the instability of grain yield in aerobic rice over seasons, the comparison between aerobic and flooded rice in crop performance has to be conducted in a long-term experiment.

In 2001, we established a long-term field experiment to compare the agronomic performance of aerobic and flooded rice using several varieties in both dry and wet seasons. The experiment has been going on for eight seasons. Our objectives were: (1) to compare crop performance between aerobic and flooded rice continuously over several seasons, and (2) to identify yield attributes responsible for yield gap between aerobic and flooded rice.

1. Materials and methods

The field experiment was conducted at the International Rice Research Institute (IRRI) farm at Los Baños, Laguna, Philippines (14°11′N, 121°15′E, 21 m asl) in both dry season (DS, January–May) and wet season (WS, June–October) from 2001 to 2004. The soil in the experiment site was Aquandic Epiaquoll with its chemical and physical properties listed in Table 1.

Three water management treatments were arranged in a randomized complete block design with four replicates. Plot size was 86 m^2. In the first six seasons (2001–2003), the three water treatments were aerobic rice in both DS and WS (T1), flooded rice in both DS and WS (T2), and aerobic in DS and flooded rice in WS (T3). Because one-season flooding in WS did not significantly change the performance of aerobic rice in DS, data of T3 from the first six seasons were not included in the comparison between aerobic and flooded rice. In 2004 DS, the flooded plots in previous six seasons (T2) were converted to aerobic plots while flooded plots only in WS (T3) became flooded. This change allowed a direct comparison between rice grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (T2, first-season aerobic rice) and in the soil where aerobic rice has been grown continuously in previous six seasons (T1, seventh-season aerobic rice). In 2004 WS, T1 became eighth-season aerobic rice, T2 became second-season aerobic rice, and T3 remained as flooded rice.

Flooded plots were puddled and kept continuously flooded from transplanting until 2 weeks before harvest. Water depth was initially 2 cm and gradually increased to 5–10 cm at full crop development. The aerobic plots were dry-ploughed and harrowed but not puddled during land preparation. One day before transplanting, aerobic plots were soaked with irrigation water to facilitate transplanting. Transplanting was used for aerobic rice to keep seedling density constant across seasons. Afterward, aerobic plots were flash irrigated with about 5 cm water each time only when the soil moisture tension at 15 cm depth reached −30 kPa. Around flowering, the threshold for irrigation was reduced to −10 kPa to prevent spikelet sterility (O'Toole and Garrity, 1984). Irrigation outlets were fitted with 6-in. PVC pipes that served as delivery channel of water for each flooded and aerobic plot. The drainage system to prevent

Table 1
Initial soil characteristics of the field experiment conducted at the International Rice Research Institute (IRRI) farm in the Philippines

Parameter	Mean	S.D.
pH	6.4	0.1
Organic C (%)	1.5	0.1
Total N (%)	0.15	0.01
Available P-Olsen (mg kg^{-1})	9.0	4.2
Available K (meq 100 g^{-1})	0.97	0.14
Active Fe (%)	2.1	0.2
Active Mn (%)	0.14	0.01
Available Zn (mg kg^{-1})	1.6	0.4
Available Cu (mg kg^{-1})	0.18	0.03
Available B (mg kg^{-1})	6.0	0.2
Exch. K (meq 100 g^{-1})	1.1	0.2
Exch. Na (meq 100 g^{-1})	1.4	0.1
Exch. Ca (meq 100 g^{-1})	21.7	0.6
Exch. Mg (meq 100 g^{-1})	13.6	0.3
Exch. Al (meq 100 g^{-1})	Nil	
EC (dS m^{-1})	0.62	0.12
CEC (meq 100 g^{-1})	37.4	1.3
Clay (%)	59.0	2.1
Silt (%)	30.8	1.4
Sand (%)	10.2	1.1

Soil samples were taken 2 days before transplanting in the dry season of 2001.

seepage of water from the flooded into the aerobic plots and the device to measure the amount of irrigation water were described by Bouman et al. (2005). Total water input (irrigation water for land preparation and for crop growth plus rainfall) was 1240–1880 mm in flooded plots and 790–1430 mm in aerobic plots. On average, aerobic plots used 190 mm less water in land preparation, and had 250–300 mm less seepage and percolation, 80 mm less evaporation, and 25 mm less transpiration than flooded plots (for details, see Bouman et al., 2005). Groundwater depth and soil moisture tension at 10–15 and 35–40 cm were also provided by Bouman et al. (2005).

An improved upland variety, Apo (formerly designated as IR55423-01) was used throughout the experiment because of its good performance under aerobic conditions (George et al., 2002; Lafitte et al., 2002). In 2004 DS, water treatments of flooded (T3) and first-season aerobic rice (T2) were divided into sub-plots to accommodate both Apo and PSBRc80, a lowland variety that is adapted to both flooded and aerobic conditions.

Twenty-one-day-old seedlings from wet bed nurseries were transplanted at the rate of three seedlings per hill at a spacing of 25 × 10 cm for both aerobic and flooded rice plots. In DS, phosphorus (60 kg P ha^{-1} as single superphosphate), potassium (40 kg K ha^{-1} as KCl), and zinc (5 kg Zn ha^{-1} as zinc sulfate heptahydrate) were applied and incorporated in all plots 1 day before transplanting. Fertilizer N in the form of urea was applied in three equal splits {50 kg ha^{-1} as basal (1 day before transplanting), at 25, and 45 days after transplanting (DAT)}. In WS, P and K input was half of that in DS while Zn was equal in both seasons. Fertilizer N was applied in three splits (20 kg ha^{-1} as basal, 20 kg ha^{-1} at 20 DAT, and 30 kg ha^{-1} at 40 DAT). Cultural management practices for achieving maximum grain yield were followed. Optimum pests and weed management practices using agro-chemicals and manual weeding were applied to achieve high yields.

Twenty hill plant samples (0.50 m^2) were taken at key growth stages for growth analysis. Plants were separated into leaf blade, stem and panicles when present. Dry matter was determined after oven-drying at 70 °C to constant weight. At maturity, 20 hills were sampled diagonally from a 5-m^2 harvest area to determine aboveground total biomass, harvest index, and yield components. Panicle number of each hill was counted to determine the panicle number per m^2. Plants were separated into straw and panicles. Straw dry weight was determined after oven-drying at 70 °C to constant weight. Panicles were hand-threshed and filled spikelets were separated from unfilled spikelets by submerging them in tap water. Three sub-samples each of 30-g filled spikelets and 2-g unfilled spikelets were taken to count the number of spikelets. Dry weights of rachis and filled and unfilled spikelets were determined after oven-drying at 70 °C to constant weight. Aboveground total biomass was the total dry matter of straw, rachis, and filled and unfilled spikelets. Spikelets per panicle, grain-filling percentage (100 × filled spikelet number/total spikelet number), and harvest index (100 × filled spikelet weight/aboveground total biomass) were calculated. Grain yield was determined from a 5-m^2 sampling area within each plot and adjusted to a moisture content of 0.14 g H_2O g^{-1} fresh weight. In 2004 DS, tissue N concentration was determined by micro-Kjeldahl digestion, distillation, and titration (Bremner and Mulvaney, 1982) to calculate aboveground total N uptake. Data were analyzed following analysis of variance (SAS, 1982) and means of water treatments were compared based on the least significant difference (LSD) Test at the 0.05 probability level. The difference between aerobic and flooded rice was calculated as 100 × (flooded rice − aerobic rice)/mean of flooded and aerobic rice.

2. Results

On the average, solar radiation was 21% greater in DS than in WS (Table 2). Both maximum and minimum temperatures were slightly higher in WS than in DS. Rainfall in WS was seven times more than in DS. Within DS or WS, variation in radiation across years was greater than that in temperatures. Variation in radiation, maximum and minimum temperatures across years was smaller in WS than in

Table 2
Average daily solar radiation, maximum temperature, minimum temperature, and accumulated total rainfall from transplanting to harvest for Apo grown under continuous aerobic conditions in dry seasons (DS) and wet seasons (WS) of 2001–2004 at IRRI farm

Season	Year	Radiation (MJ m^{-2} d^{-1})	Maximum temperature (°C)	Minimum temperature (°C)	Total rainfall (mm)
Dry	2001	18.5	30.5	24.0	265
	2002	20.4	30.3	23.1	58
	2003	22.1	31.4	23.6	92
	2004	20.4	31.2	23.7	91
Mean		20.4	30.9	23.6	127
Wet	2001	16.8	31.3	24.5	777
	2002	17.2	31.2	24.5	1142
	2003	17.6	31.5	24.6	761
	2004	15.9	31.4	24.2	854
Mean		16.9	31.4	24.5	884

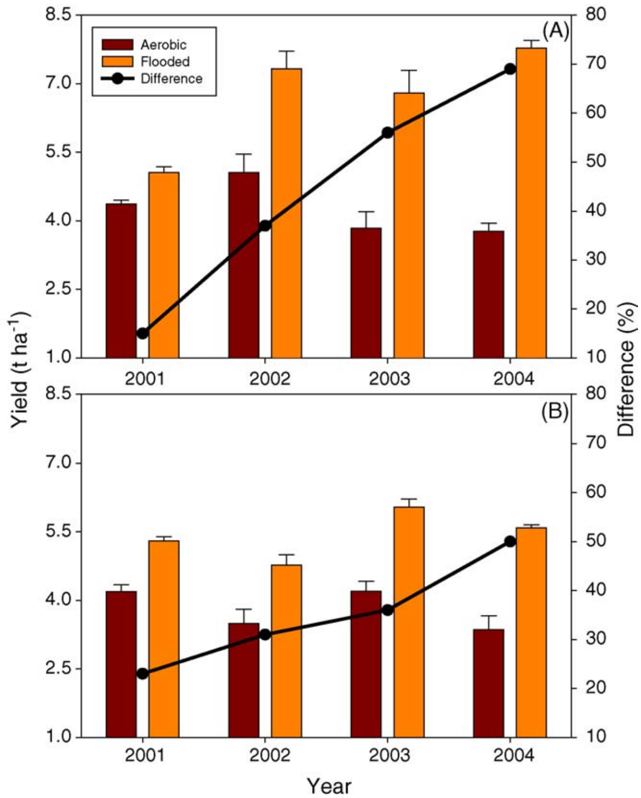

Fig. 1. Grain yield of Apo grown under aerobic and flooded conditions and the yield difference between aerobic and flooded rice in dry seasons (A) and wet seasons (B) of 2001–2004 at IRRI farm.

DS. In DS, low radiation and high minimum temperature were observed in 2001. Radiation was highest in 2003 among the four DS while it was lowest in 2004 among the four WS.

Aerobic rice produced significantly lower grain yields than flooded rice throughout the experiment (Fig. 1). There was no clear trend in grain yield in aerobic rice over the eight seasons. However, the yield gap between aerobic and flooded rice widened as the number of cropping seasons increased in both DS and WS. In DS, the difference in grain yield between aerobic and flooded rice was 15% in 2001 and increased to 69% in 2004. In WS, the difference increased from 23% in 2001 to 50% in 2004. The difference in grain yield between aerobic and flooded rice was consistently greater in DS than in WS in 2002–2004. These results indicate that significant yield decline of continuous aerobic rice appeared in the second year (2002) and became more severe as the number of cropping seasons increased.

Flooded rice produced more aboveground total biomass than aerobic rice (Table 3), but the difference started to be statistically significant in the third season (2002 DS). The difference between aerobic and flooded rice in aboveground total biomass gradually widened as the number of cropping seasons increased. This was also supported by the difference in seasonal patterns of biomass accumulation between aerobic and flooded rice across all eight seasons (Fig. 2). There was no significant difference between aerobic and flooded rice in biomass production in the early vegetative stage up to midtillering in the first five seasons. The significant difference in biomass production occurred at midtillering starting in the sixth season. In general, the difference in biomass accumulation between aerobic and flooded rice was greater and occurred earlier in DS than in WS.

Flooded rice had higher harvest index than aerobic rice, but the difference was not statistically different in 2001 WS and 2004 WS (Table 3). Unlike biomass production, there was no increasing trend in the differences in harvest index between aerobic and flooded rice as the number of cropping seasons increased. The difference between aerobic and flooded rice in harvest index was consistently smaller than in biomass production. Therefore, the yield gap between aerobic and flooded rice was attributed more to the difference in biomass production than in harvest index.

Flooded rice produced significantly more panicles than aerobic rice except in 2001 WS and 2002 DS (Table 4). Spikelet number per panicle was greater in flooded rice than in aerobic rice except in 2001 DS. Flooded rice consistently produced more spikelets per m^2 than aerobic rice, but the difference was not statistically significant in 2001 WS. Aerobic rice had lower grain filling percentage than flooded rice in all eight seasons. The differences in the first four

Table 3
Aboveground total biomass and harvest index of Apo grown under aerobic and flooded conditions in dry seasons (DS) and wet seasons (WS) of 2001–2004 at IRRI farm

Treatment	2001 DS	2001 WS	2002 DS	2002 WS	2003 DS	2003 WS	2004 DS	2004 WS
Aboveground total biomass (g m^{-2})								
Aerobic	1091 a[a]	1162 a	1215 b	879 b	957 b	1040 b	862 b	809 b
Flooded	1202 a	1262 a	1536 a	1196 a	1534 a	1405 a	1604 a	1189 a
Difference (%)	10	8	23	31	46	30	60	38
Harvest index (%)								
Aerobic	38.4 b	41.1 a	41.0 b	39.5 b	42.1 b	39.8 b	45.4 b	44.1 a
Flooded	41.7 a	42.5 a	45.1 a	44.4 a	47.1 a	42.6 a	47.1 a	46.2 a
Difference (%)	8	3	10	12	11	7	4	5

[a] Within a column for each parameter, means followed by different letter are significantly different at 0.05 probability level according to least significant difference (LSD) test.

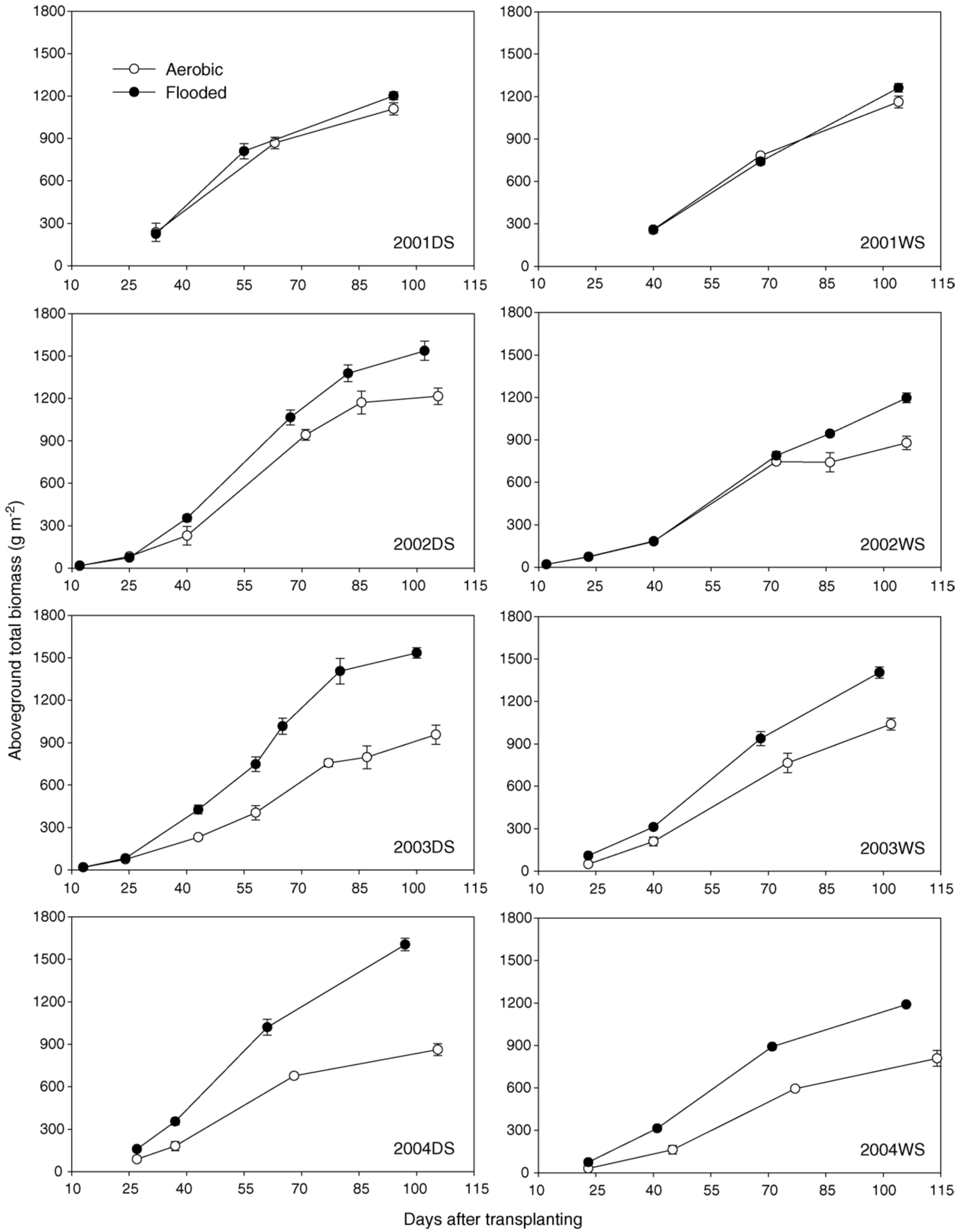

Fig. 2. Aboveground total biomass of Apo grown under aerobic and flooded conditions in dry seasons (DS) and wet seasons (WS) of 2001–2004 at IRRI farm. Vertical bars represent standard error of mean and sometimes are smaller than the symbols.

seasons were not statistically significant and the difference was smaller than in the last four seasons. Aerobic rice also had lower 1000-grain weight than flooded rice except in 2003 WS. Flooded rice showed more consistent 1000-grain weight across seasons than aerobic rice. There was no increasing trend in the differences in any yield component between aerobic and flooded rice as the number of cropping seasons increased. Yield gap between aerobic and flooded

Table 4
Yield components of Apo grown under aerobic and flooded conditions in dry seasons (DS) and wet seasons (WS) of 2001–2004 at IRRI farm

Treatment	2001 DS	2001 WS	2002 DS	2002 WS	2003 DS	2003 WS	2004 DS	2004 WS
Panicles m^{-2}								
Aerobic	196 b[a]	208 a	296 a	188 b	307 b	235 b	270 b	204 b
Flooded	240 a	208 a	300 a	230 a	356 a	260 a	347 a	226 a
Difference (%)	20	0	1	20	15	10	25	10
Spikelets $panicle^{-1}$								
Aerobic	120 a	130 b	108 b	129 b	97 b	119 b	100 b	120 a
Flooded	112 a	140 a	131 a	143 a	123 a	150 a	114 a	127 a
Difference (%)	−7	7	19	10	24	23	13	6
Spikelets m^{-2} ($\times$1000)								
Aerobic	23.4 b	26.8 a	31.6 b	24.3 b	29.9 b	28.0 b	26.9 b	24.5 b
Flooded	26.7 a	28.9 a	39.3 a	32.7 a	43.6 a	38.8 a	39.3 a	28.6 a
Difference (%)	13	8	22	29	37	32	37	15
Grain filling (%)								
Aerobic	80.9 a	77.8 a	77.7 a	66.4 a	72.5 b	66.5 b	79.0 b	70.8 b
Flooded	84.0 a	80.0 a	82.1 a	72.8 a	80.4 a	70.6 a	87.4 a	85.1 a
Difference (%)	4	3	6	9	10	6	10	18
1000-grain weight (g)								
Aerobic	22.0 b	22.8 b	20.3 b	21.5 b	18.5 b	22.3 a	18.5 b	20.6 b
Flooded	22.3 a	23.2 a	21.5 a	22.4 a	20.7 a	21.8 b	22.0 a	22.6 a
Difference (%)	1	2	6	4	11	-2	17	9

[a] Within a column for each parameter, means followed by different letter are significantly different at 0.05 probability level according to least significant difference (LSD) test.

rice was attributed greatly to the difference in sink formation and moderately to the difference in grain filling percentage and 1000-grain weight.

The first-season aerobic rice produced 68% higher grain yield than the seventh-season aerobic rice in 2004 DS, which confirmed the yield decline of continuous aerobic rice (Table 5). The yield difference was associated with total biomass production. Panicle number, spikelet number per panicle, and 1000-grain weight contributed to the yield difference. There was no significant difference in harvest index and grain filling percentage between the first- and seventh-season aerobic rice. Flooded rice produced 106% higher grain yield than the seventh-season aerobic rice in 2004 DS. All yield attributes were significantly different between flooded rice and the seventh-season aerobic rice, especially biomass production, panicle number, and 1000-grain weight. When compared with the first-season aerobic rice, flooded rice yielded 23% higher than aerobic rice mainly due to higher biomass production, more panicles, better grain filling, and greater 1000-grain weight. Flooded rice had smaller difference from the first-season aerobic rice in seasonal biomass accumulation and crop N uptake than from the seventh-season aerobic rice (Fig. 3). When a variety (PSBRc80) that was adapted to both flooded and aerobic conditions was used in 2004 DS, the difference in grain yield between flooded and the first-season aerobic rice was 8% and statistically insignificant (Table 6). The differences in yield attributes between flooded and the first-season aerobic rice were also statistically insignificant except for 1000-grain weight in PSBRc80.

Table 5
Grain yield and yield components of Apo grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (first-season aerobic rice) or in the soil where aerobic rice has been grown continuously in previous six seasons (seventh-season aerobic rice) in comparison with flooded rice in the dry season of 2004 at IRRI farm

Parameters	First-season aerobic rice (A_{1st})	Seventh-season aerobic rice (A_{7th})	Flooded rice (F)	Difference (%)		
				A_{1st} vs. A_{7th}	A_{1st} vs. F	A_{7th} vs. F
Grain yield (t ha^{-1})	6.32 b[a]	3.77 c	7.78 a	51	21	69
Total biomass (g m^{-2})	1343 b	862 c	1604 a	44	18	60
Harvest index (%)	45.3 b	45.4 b	47.1 a	0	4	4
Panicles m^{-2}	313 b	270 c	347 a	15	10	25
Spikelets $panicle^{-1}$	117 a	100 b	114 a	16	−3	13
Spikelets m^{-2} ($\times$1000)	36.5 a	26.9 b	39.3 a	30	7	37
Grain filling (%)	80.9 b	79.0 b	87.4 a	2	8	10
1000-Grain weight (g)	20.6 b	18.5 c	22.0 a	11	7	17

[a] Within a row, means followed by different letter are significantly different at 0.05 probability level according to least significant difference (LSD) test.

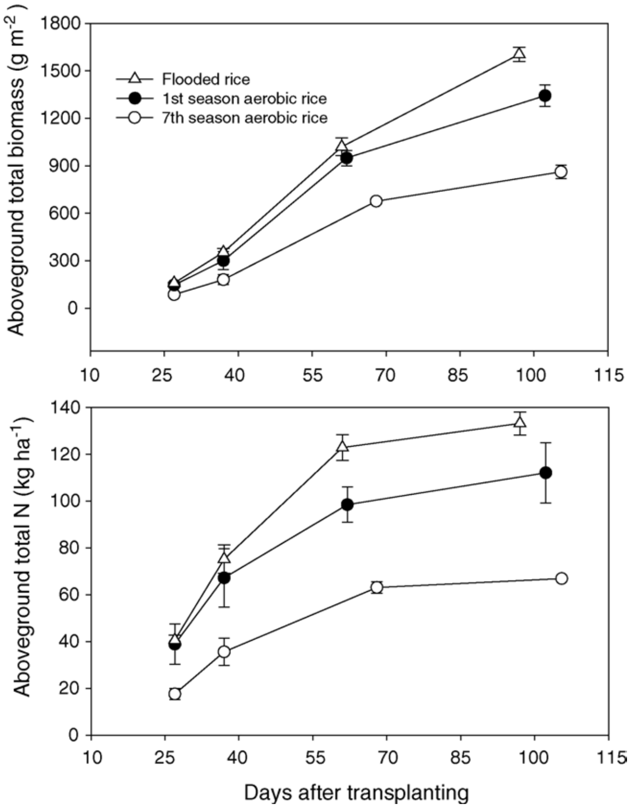

Fig. 3. Aboveground total biomass and N uptake of Apo grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (first-season aerobic rice) or in the soil where aerobic rice has been grown continuously in previous six seasons (seventh-season aerobic rice) in comparison with flooded rice in the dry season of 2004 at IRRI farm.

3. Discussion

The yield difference between aerobic and flooded rice ranged from 8 to 69% depending on the number of seasons that aerobic rice has been continuously grown, dry and wet seasons, and varieties. When the first-season aerobic rice was compared with flooded rice, the yield difference was 15–21% for Apo. One would argue that Apo is an upland variety and may not yield well under flooded lowland conditions. Therefore, the difference between aerobic and flooded rice was small for Apo. In 2004 DS, we included a variety, PSBRc80, that is adapted to lowland conditions. The difference in yield between the first-season aerobic rice and flooded rice for PSBRc80 was only 8% and statistically insignificant. The yield gap between aerobic and flooded rice widened as the number of cropping seasons increased. The maximum yield gap occurred in the seventh season (2004 DS) when the difference between the seventh-season aerobic rice and flooded rice reached 69% in Apo. In general, the difference in yield between aerobic and flooded rice was greater in DS than in WS, which was associated with difference in the soil water status of aerobic rice between DS and WS (Bouman et al., 2005). The soil was wetter in WS because of more frequent rains than in DS (Table 2).

Table 6
Grain yield and yield components of PSBRc80 grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (first-season aerobic rice) and under flooded conditions in the dry season of 2004 at IRRI farm

Parameters	First-season aerobic rice	Flooded rice	Difference (%)
Grain yield (t ha^{-1})	7.22 a[a]	7.84 a	8
Total biomass (g m^{-2})	1339 a	1497 a	11
Harvest index (%)	46.7 a	47.5 a	2
Panicles m^{-2}	424 a	465 a	9
Spikelets $panicle^{-1}$	92 a	89 a	−3
Spikelets m^{-2} (×1000)	38.7 a	41.1 a	6
Grain filling (%)	78.6 a	80.0 a	2
1000-Grain weight (g)	20.6 b	21.6 a	5

[a] Within a row, means followed by different letter are significantly different at 0.05 probability level according to least significant difference (LSD) test.

The yield difference between aerobic and flooded rice was attributed more to biomass production than to harvest index. Among yield components, sink size (spikelets per m^2) contributed more to the yield gap between aerobic and flooded rice than grain filling percentage and 1000-grain weight. In general, flooded rice produced more panicles with more spikelets per panicle than aerobic rice. Like grain yield, the difference in yield attributes between the first-season aerobic rice and flooded rice was small.

Rapid yield decline was reported under continuous upland rice cropping (Ventura and Watanabe, 1978) and under monocropping of aerobic rice (George et al., 2002) in the Philippines. Yield declined by 30–60% in the second season under continuous upland rice cropping for variety IR2061-464-2-4 (Ventura and Watanabe, 1978). Grain yield decreased by up to 73% in the third season compared to the second season under monocropping of aerobic rice for variety UPLRi-5 (George et al., 2002). In this study, the yield decline of continuous aerobic rice was determined in three ways. The first way was to compare the absolute yield across seasons. In DS, the yield decline occurred in the third year and it decreased by 25% from 2002 to 2003. In WS, there was no clear trend in yield over the 4 years. The second way was to compare the relative yield of aerobic rice to flooded rice across seasons. The relative grain yield was used in order to minimize the effect of seasonal variation in solar radiation and air temperatures. For example, 2002 DS and 2003 DS had greater solar radiation and lower nighttime temperature than 2001 DS (Table 2). Therefore, flooded rice produced about 2 t ha^{-1} more grain in 2002 DS and 2003 DS than in 2001 DS. As the number of cropping seasons increased, the relative yield of aerobic rice to flooded rice decreased (i.e. yield difference between aerobic and flooded rice increased). Assuming that flooded rice has stable yield and only climate has effect on its yield, increasing yield gap between aerobic and flooded rice implied a yield decline of continuous aerobic rice. The difference in grain yield between aerobic and flooded rice increased from 15% in 2001 to 69% in 2004 in DS and from 23 to 50% over the same period in WS, suggesting that the yield of continuous aerobic rice declined by 44% in DS and 24% in WS from 2001 to 2004. The third way was to directly compare the yields in the same growing season between rice grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (first-season aerobic rice) and in the soil where aerobic rice has been grown continuously in previous six seasons (seventh-season aerobic rice). The yield difference between first- and seventh-season aerobic rice was 2.55 t ha^{-1} for Apo in 2004 DS, indicating that the yield declined by 40% from yield level of 6.32 t ha^{-1} in the first season after seven seasons of continuous monocropping of aerobic rice. Soil test did not explain the difference in grain yield between first- and seventh-season aerobic rice (data not shown). Compared with previous studies (Ventura and Watanabe, 1978; George et al., 2002), the magnitude of yield loss under continuous aerobic rice was smaller in this study. This was probably due to the differences in soil and varieties used. The causes of yield decline in continuous aerobic rice remain unknown. It could be related to the build-up of nematodes and soil pathogens under aerobic conditions (Ventura et al., 1981; Lafitte et al., 2002). Changes in soil mineral nutrients (Lin et al., in press) and growth inhibition by toxic substances from root residues (Nishio and Kusano, 1975) could also cause the yield decline.

Total water use and water productivity of aerobic rice was 27–51% lower and 32–88% higher than that of flooded rice, respectively (Bouman et al., 2005). However, the large yield gap between aerobic and flooded rice and the yield loss of continuous aerobic rice could outweigh the benefits of its water savings. Our results have demonstrated that the yield gap can be narrowed by developing varieties that are more adapted to aerobic conditions such as PSBRc80. Crop management strategies could be developed to reverse the yield decline of continuous aerobic rice only after the causes of yield decline are identified. New aerobic rice varieties with minimum yield gap compared with flooded rice and crop management strategies that can reverse the yield decline of continuous aerobic rice have to be developed before aerobic rice technology can be adopted in large areas in the tropics.

References

Barker, R., Dawe, D., Tuong, T.P., Bhuiyan, S.I., Guerra, L.C., 1999. The outlook for water resources in the year 2020: challenges for research on water management in rice production. In: Assessment and Orientation towards the 21st Century. Proceedings of the 19th session of the International Rice Commission, 7–9 September 1998, Cairo, Egypt. Food, Agriculture Organization, pp. 96–109.

Borell, A., Garside, A., Shu, F.K., 1997. Improving efficiency of water for irrigated rice in a semi-arid tropical environment. Field Crops Res. 52, 231–248.

Bouman, B.A.M., Peng, S., Castañeda, A.R., Visperas, R.M., 2005. Yield and water use of irrigated tropical aerobic rice systems. Agric. Water Manage. 74, 87–105.

Bouman, B.A.M., Tuong, T.P., 2001. Field water management to save water and increase its productivity in irrigated rice. Agric. Water Manage. 49, 11–30.

Bouman, B.A.M., Wang, H., Yang, X., Zhao, J., Wang, C., 2002. Aerobic rice (Han Dao): a new way of growing rice in water-short areas. In: Proceedings of the 12th International Soil Conservation Organization Conference, 26–31 May, 2002, Beijing, China. Tsinghua University Press, pp. 175–181.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-total. In: Page, A.L., et al. (Eds.), Methods of Soil Analysis, Part 2. Am. Soc. Agron., Madison, Wisconsin, pp. 595–624.

De Datta, S.K., Krupp, H.K., Alvarez, E.I., Modgal, S.C., 1973. Water management in flooded rice. In: Water Management in Philippine Irrigation Systems: Research and Operations, International Rice Research Institute, Los Baños, Philippines, pp. 1–18.

George, T., Magbanua, R., Garrity, D.P., Tubaña, B.S., Quiton, J., 2002. Rapid yield loss of rice cropped successively in aerobic soil. Agron. J. 94, 981–989.

Guimaraes, E.P., Stone, L.F., 2000. Current status of high-yielding aerobic rice in Brazil. In: Proceedings of the Paper Presented at the Aerobic Rice Workshop, 7–8 September, International Rice Research Institute, Los Baños, Philippines.

International Water Management Institute (IWMI), 2000. IWMI Global Water Scarcity Study. International Water Management Institute, Colombo, Sri Lanka.

Lafitte, R.H., Courtois, B., Arraudeau, M., 2002. Genetic improvement of rice in aerobic systems: progress from yield to genes. Field Crops Res. 75, 171–190.

Li, Y., 2001. Research and practice of water-saving irrigation for rice in China. In: Barker, R., Li, Y., Tuong, T.P. (Eds.), Water-Saving Irrigation for Rice. Proceedings of the International Workshop, 23–25 March 2001, Wuhan, China. International Water Management Institute, Colombo, Sri Lanka, pp. 135–144.

Lin, S., Dittert, K., Sattelmacher, B., 2002. The Ground Cover Rice Production System (GCRPS)—a successful new approach to save water and increase nitrogen fertilizer efficiency? In: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Bindraban, P.S., Tuong, T.P., Ladha, J.K. (Eds.), Water-wise Rice Production. Proceedings of the International Workshop on Water-wise Rice Production, 8–11 April 2002, Los Baños, Philippines. International Rice Research Institute, Los Baños, Philippines, pp. 187–196.

Lin, S., Li, J., Sattelmacher, B., Brueck, H., in press. Lowland and aerobic rice respond differently to ammonium and nitrate supply during early growth stages. J. Plant Nutr. 28.

Nishio, M., Kusano, S., 1975. Effect of root residues on the growth of upland rice. Soil Sci. Plant Nutr. 21, 391–395.

O'Toole, J.C., Garrity, D.P., 1984. Upland Rice Soil–Plant–Water Relationships. An Overview of Upland Rice Research. IRRI, Los Baños, Philippines, pp. 394–411.

SAS Institute, 1982. SAS User's Guide: Statistics, 4th ed. SAS Inst., Cary, NC.

Stoop, W., Uphoff, N., Kassam, A., 2002. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agric. Syst. 71, 249–274.

Tabbal, D.F., Bouman, B.A.M., Bhuiyan, S.I., Sibayan, E.B., Sattar, M.A., 2002. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric. Water Manage. 56, 93–112.

Tuong, T.P., Bouman, B.A.M., 2003. Rice production in water-scarce environments. In: Proceedings of the Water Productivity Workshop. 12–14 November 2001, Colombo, Sri Lanka. International Water Management Institute, Colombo, Sri Lanka.

Ventura, W., Watanabe, I., 1978. Growth inhibition due to continuous cropping of dryland rice and other crops. Soil Sci. Plant Nutr. 24, 375–389.

Ventura, W., Watanabe, I., Castillo, M.B., dela Cruz, A., 1981. Involvement of nematodes in the soil sickness of a dryland rice-based cropping system. Soil Sci. Plant Nutr. 27, 305–315.