Irrigation management effects on yield and water productivity of hybrid, inbred and aerobic rice varieties in China

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ABSTRACT

The objective of this study was to compare the effects of different water saving irrigation regimes on yield, irrigation input and water productivity of aerobic (high yielding rice variety that can be grown in non-puddled soil without flooding) and lowland (hybrid and inbred) rice varieties in different water table conditions. Experiments were carried out in Tuanlin, Hubei Province and in Huibei, Henan Province in China in 2001 and 2002. The tested water treatments were continuous flooding (CF), alternate wetting and drying (AWD), flush irrigation (FI) with different threshold soil water potentials (at which irrigation was applied) of –10, –30, and –70 kPa and partially rainfed (PRF). The varieties used were hybrid 2you725 (Tuanlin) or inbred 90247 (Huibei), and aerobic rice HD502 (both sites).

The tested aerobic variety yielded satisfactory in Huibei, its yield was however significantly less than the lowland varieties. But in Tuanlin, it suffered heavy stem borer infestation in 2001 and by high spikelet sterility in 2002. The response of yield, and water productivity to irrigation regimes depended on the depth of the groundwater. Rice yields did not differ significantly among water treatments when the water table was shallow. When the water table was deep (Huibei, 2002), yield declined with decreasing threshold soil water potentials, especially with the lowland variety. CF had the highest irrigation water inputs, followed by AWD and FI. Among the FI treatments in 2002, water input declined sharply when the threshold soil water potentials were reduced from –10 to –70 kPa. Treatments with lower threshold soil water potentials had significantly higher water productivities than that at –10 kPa.

Keywords: alternate wetting and drying, flush irrigation, water productivity

1. INTRODUCTION

Rice is the staple food of China and accounts for about 35% of the annual grain production. Population continues to increase by about 13 million per year. Rice production still need to increase to meet consumption demand without resort to imports (Rice Almanac, IRRI 2002). More than 90% of the total rice production is contributed by irrigated rice areas. Due to the rapid industrialization and increase in population, competition for water among agricultural, domestic and industrial water users is increasing. It is expected that in the near future, less water will be available for rice cultivation (Tuong and Bouman, 2002). Thus, water saving in rice cultivation is essential to maintain food security in China.

Several water-saving irrigation (WSI) techniques for rice have been reported previously (Bouman 2001, Bouman and Tuong 2001). The most widely adopted water-saving practice in China is alternate wetting and drying (AWD) (Mao Zhi 1993, Li 2001, Xu Zhifang 1982). The rice field is allowed to dry for a few days in between irrigation events, including a midseason drainage in which the field is allowed to dry for 7–15 days at the end of the tillering stage. Tabbal et al (2002) reported reduced water inputs and increased water productivity of rice grown under just-saturated soil conditions compared with traditional flooded rice. It has been suggested that rice could be grown aerobically under irrigated conditions just like upland crops, such as wheat or maize (Bouman 2001). The aerobic condition is maintained by using flush irrigation (FI) or sprinklers so that ponding occurs for only short periods of time just after irrigation or rain. The potential of WSI to reduce water inputs and its effect on yield and water productivity depend on soil type, groundwater table depth, and climate (Bouman and Tuong 2001).

Though the potential for water savings of aerobic cultivation is large, aerobic cultivation using conventional lowland rice varieties almost always leads to a yield reduction (De Datta et al 1973, McCauley 1990, Westcott and Vines 1986). A special type of rice, dubbed aerobic variety (Bouman (2001) is required to produce high yields in nonpuddled and unsaturated (aerobic) soil.. It is responsive to high inputs, can be rainfed or irrigated, and tolerates occasional flooding. A first generation of high-yielding aerobic rice varieties has been developed successfully over the last 20 years in North China (Wang Huaqi et al, 2002). However, the trade-off between yield reduction and water savings compared with flooded lowland rice is still unknown (Yang Xiaoguang et al, 2002). The potential of the newly developed aerobic rice varieties and the effects of WSI on rice yield and water productivity have not been studied in Central China.

It is hypothesized that (1) aerobic rice varieties can be grown and water saving technologies can be applied in Central China to increase water productivity of rice cultivation, and (2) the effects of irrigation regimes on water inputs, grain yield, and water productivity vary with different groundwater depths and nutrient availability. The objective of this study was to compare the effects of different water saving irrigation regimes and nitrogen treatments on yield, irrigation input and water productivity of aerobic and lowland (hybrid and inbred) rice varieties in different water table conditions at two sites in Central China.

2. METHODOLOGY

2.1 Experimental sites

The experiments were conducted at Kaifeng, Hennan Province and Tuanlin, Hubei Province, China in 2001 and 2002. The experiments in both sites in 2001 were in locations with high water table. In 2002, the experiments were moved to locations with deeper groundwater table.

The average annual rainfall and soil conditions at the experiment sites are given in Table 1.

Table 1. Average annual rainfall and soil characteristics of 20 cm layer at the experimental sites in 2001 and 2002.

	Huibei, Henan Province		Tuanlin, Hubei Province	
	2001-location	2002-location	2001-location	2002-location
Average annual rainfall (mm)	600		900	
Soil type	loam	sandy loam	clay loam	silt loam
pH (1:1 H_2O)	n.a.	8.45	6.5	6.74
Organic carbon (%)	n.a.	0.78	1.03	1.72
Available N (mg kg^{-1})	n.a.	67.9	5.8	122.4
CEC (cmol kg^{-1})	n.a.	85.4	20.6	152.5

n.a. = not available

2.2 Experimental design and treatments

2.2.1 In Tuanlin

The experiments were conducted in split-split-plot design with three replications in 2001 and 2002. All fields were kept flooded with 2 – 5 cm water depth at transplanting and during the transplanting shock recovery (about 10 days after transplanting, DAT). Thereafter, the following water treatments were applied to the main plots:

1. *Alternate wetting and drying* (AWD) *in puddled soil*: The rice field was let dry for several days after the disappearance of the surface water layer before irrigation was applied, as described in Cabangon et al. 2001. This was farmer's practice in Tuanlin.
2. *Flushing irrigation* (FI-50) *in non-puddled soil*. Plots were irrigated quickly with large depth of water (about 40 –80 mm) and until the whole surface is covered with water. Water quickly disappeared after irrigation. The field was irrigated again when soil dries out until soil water potential at 20-cm depth is about –50 kPa.
3. *Partially Rainfed* (PRF) *in puddled soil*. No irrigation water was applied after 10 DAT.

The subplots consisted of two rice varieties (V): A commonly grown hybrid rice, 2you725 (V_1), and an aerobic rice, HD502 (V_2). The hybrid rice was transplanted using 41-d-old seedlings at 2 plants hill^{-1} in 20 × 20-cm spacing. The transplanted aerobic rice used 29-d-old seedlings at 4 plants hill^{-1} in 27 × 13-cm spacing. The spacing was carefully selected using local experience and expert knowledge (Wang Huaqi, personal communication for aerobic rice)The sub-subplots consisted of 2 Nitrogen application rates (N): No N-fertilizer (N_0) and 180 kg N ha^{-1} (N_{180}) applied in 4 splits 30% as basal, 30% at 10 DAT; 30% at PI and 10% at heading. 70 kg P ha^{-1} and 70 kg K ha^{-1}. All P (70 kg ha^{-1}) and K (70 kg ha^{-1}) were applied as basal.

2.2.2 In Huibei

The experiments were conducted in a split-plot design, with three replicates in 2001 and four replicates in 2002. In 2001, the main plots were water treatments, in which fields were kept flooded with 2 and 5-cm water depth during the transplanting recovery period, for about 10 and 17 days after transplanting (DAT). Then the following water treatments were applied as follows:

In 2001, the three water treatments were

1. *Continuous flooding* (CF) *in puddled soil*. The field water level was maintained from 2 to 10 cm. This was the farmers' practice in Kaifeng.

2. *Alternate wetting and drying* (AWD) *in puddled soil.* same as in Tuanlin
3. *Flush irrigation* (FI-50) *in nonpuddled, aerobic soil.* same as in Tuanlin

In 2002, the water treatments were three flush irrigation (FI) methods with different threshold soil water potentials: −10 kPa (FI-10), −30 kPa (FI-30), and −70 kPa (FI-70). A fourth treatment of "partially rainfed with survival irrigation" (PRF) was included where irrigation was withheld until the rice crop showed very severe drought symptoms.

The subplots consisted of two varieties: a commonly grown inbred rice, 90247 (V_1), and an aerobic rice, HD502 (V_2).. The inbred rice was transplanted using 37-d-old seedlings at 6 plants hill^{-1} in 20 × 20-cm spacing. The transplanted aerobic rice used 27-d-old (2001) and 38-d-old seedlings (2002) at 4 plants hill^{-1} in 27 × 13-cm spacing.

The nitrogen (N) fertilizer (180 kg N ha^{-1} in 2001 and 225 kg N ha^{-1} in 2002) was applied in four splits: 30% basal, 30% at 10 DAT, 30% at panicle initiation (PI), and 10% at heading. In addition, 70 kg P ha^{-1} (in 2001) and 50 kg P ha^{-1} (in 2002) and 70 kg K ha^{-1} were applied as basal application. Basal fertilizer was broadcast and incorporated into the soil during the last land preparation (harrowing). The topdressings were applied on the soil surface just before irrigation.

2.3 Climatic, Soil, and Water Data Measurements

Daily meteorological parameters (rainfall, pan evaporation, sunshine hours, temperature—minimum and maximum—and wind speed) were collected from meteorological stations at the Huibei experiment station some 8 km away from the site in 2001 and 1 km from the 2002 site. In Tuanlin, the weather station was a few hundred meters from the experiment sites.

Irrigation water inputs were monitored using flow meters at each irrigation. In Tuanlin, irrigation amounts were measured in each sub-subplot. In Huibei, measurements were taken in the main plots in 2001 and in all subplots in 2002. Standing water depth was measured daily using meter gauges in all plots. However, in Huibei in 2002, this could not be measured because standing water quickly subsided right after irrigation or rainfall.

Percolation rings were installed in each of the AWD and PRF plots to quantify the daily percolation rate. It was assumed that there was no percolation during days without standing water In Huibei 2002, daily percolation rate were not measured because there was no continuous standing water in the field. The seasonal percolation was computed from the summation of daily percolation rate. Groundwater depth was measured in each replicate once to twice weekly in 2001 and daily in 2002.

The water balance components (expressed in mm of water) in the field were computed according to

$$R + I - D - ET - S\&P = \Delta S \qquad (1)$$

Where R = rainfall; I = irrigation; D = Surface drainage, calculated from the difference in the ponded water depth before and after drainage; ET = evapotranspiration, computed from weather data using the Penman equations (Allen et al 1998) and crop factors, k_c, of rice for China (Mao Zhi, 1992); ΔS = change in water storage in the field, assumed to be negligible compared with other water balance components; S&P = seepage and percolation. estimated as the closure term in the water balance over the whole season. Note that, in this calculation, the computed S&P incorporates the error term and, implicitly, any capillary rise. When P was measured (e.g. In Tuanlin 2001), we could separate S and P, the seasonal seepage became the closure term in the water balance equation over the whole season. In Huibei, the aerobic rice variety had a shorter duration than the inbred rice, but, in both years, no irrigation and drainage occurred after harvesting of the aerobic variety, and the above water balance components were the same for both varieties. Further details of the hydrological measurement procedures can be found in Cabangon et al (2001).

2.4 Rice Yield and water productivity

At maturity, we measured grain yield from 6-7 m^2 (depending on the variety) harvest areas. Sub samples were used for determining yield components (1,000-grain weight, spikelet number, panicle number, filled spikelet number). Water productivity (kg grain m^{-3} water) was calculated as the weight of grain produced per unit of irrigation water from transplanting to harvest (WPI), or per unit of total water (irrigation + rainfall) from transplanting to harvest (WP_{I+R}).

3. RESULTS

3.1 Climatic and agrohydrological conditions

Rainfall, evaporation, sunshine hours from transplanting to harvest are shown in Table 2. The data were distinguished between V_1 and V_2 because they had different transplanting dates and crop growth duration. In Tuanlin, rainfall during the crop growth period was lower in 2001 compared to 2002. However, seasonal evaporation was higher in 2001 than in 2002 which conforms to higher solar radiation in 2001. In Huibei, seasonal rainfall was higher in 2001 compared to 2002. There were no differences in evaporation between the two years. Sunshine hours were higher in 2002 than in 2001 and higher in V_1 than in V_2 because of its longer crop growth period.

In 2001, rainfall was lower in Tuanlin compared to Huibei during the crop season, but the reverse is true for 2002. There were no differences in seasonal evaporation between the two sites. However, the daily average evaporation rate was higher in Tuanlin (3.9 to 4.3 mm d^{-1}) than in Huibei (3.7 to 3.9 mm d^{-1}). This conformed to higher sunshine duration in Tuanlin than in Huibei. In 2002, rainfall was lower in Huibei than in Tuanlin.

In 2001, mean groundwater table depth was around 20-50 cm from field surface until about 3 wks before harvesting at both sites. Groundwater table declined to about 60 – 90 cm at harvest (Fig. 1). In 2002, the groundwater table depth was relatively deeper. However, in Tuanlin, the mean groundwater table fluctuated due to irrigation or rainfall (Fig. 1a) and did not go down below 90 cm depth. In Huibei 2002-site, the groundwater table changed from 200-cm depth at transplanting to about 350-cm depth at harvest (Fig. 1b).

3.2 Water depth

Figure 2 gives the dynamics of field water depth in AWD and FI-50 at Tuanlin in 2001 and 2002 (PRF had intermediate values and are not shown). Field water depths were similar from transplanting to about mid-tillering. Afterwards, alternate flooded and non-flooded conditions were observed in 2001. However, in 2002 it was difficult to maintain standing water due to seepage of water to the drains resulting to lesser number of days with standing water in 2002 (Table 3).

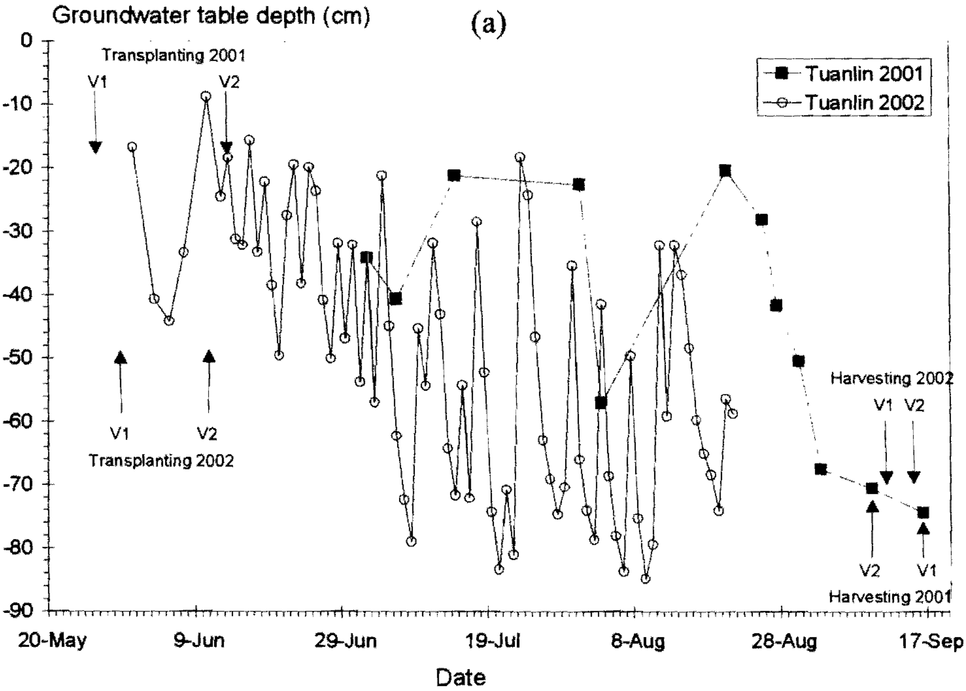
Table 2. Climatic data and crop duration from transplanting to harvesting at Tuanlin, Hubei Province and Huibei, Hennan Province, 2001 and 2002.

Year	Site	Variety[a]	Rainfall (mm)	Evaporation (mm)	Sunshine (h)	Duration (d)
2001	Tuanlin	V1	297	434	769	110
		V2	221	409	716	96
	Huibei	V1	360	437	427	119
		V2	354	398	360	103
2002	Tuanlin	V1	363	343	668	110
		V2	325	291	555	91
	Huibei	V1	267	427	532	115
		V2	266	393	498	107

[a]V1 = hybrid (Tuanlin) or inbred variety (Huibei), V2 = aerobic variety

Figure 3 shows the field water depths in Huibei in 2001. There was a clear difference in field water depths among the water treatments. Flooding was maintained in the continuously flooded treatment, while there were periods without standing water in the others, resulting in greater number of days with standing water in the CF and AWD than in FI-50 (Table 4). The number of days with ponded water during the crop season was highest in CF followed by AWD then by FI-50 (Table 4). The AWD treatment almost always had some floodwater and FI-50 was generally only non-flooded after flowering. Even then, the water table never went deeper than 6 cm (Fig. 1b) and aerobic soil conditions were barely obtained.

In 2002, when the experiment was moved to a site with deep groundwater table, it was not possible to maintain ponded water in the field, except for a few hours after the flush irrigations. Thus, the number of days with standing water refers also to the number of irrigations. In Table 4, the number of days with standing water during the crop season declined as the threshold soil water potential decreased. Except for the FI-10 treatment, a large portion of days with ponded water occurred during the transplanting recovery period.



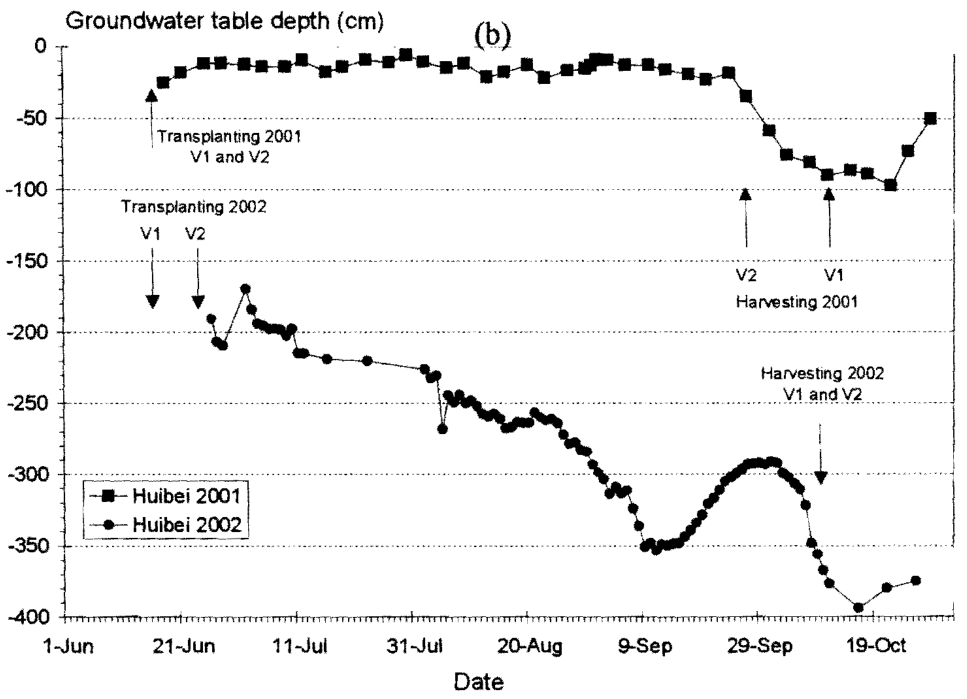


Fig. 1. Mean groundwater table depth in (a) Huibei and (b) Tuanlin, in 2001 and 2002. V1 = inbred rice variety; V2 = aerobic rice variety.

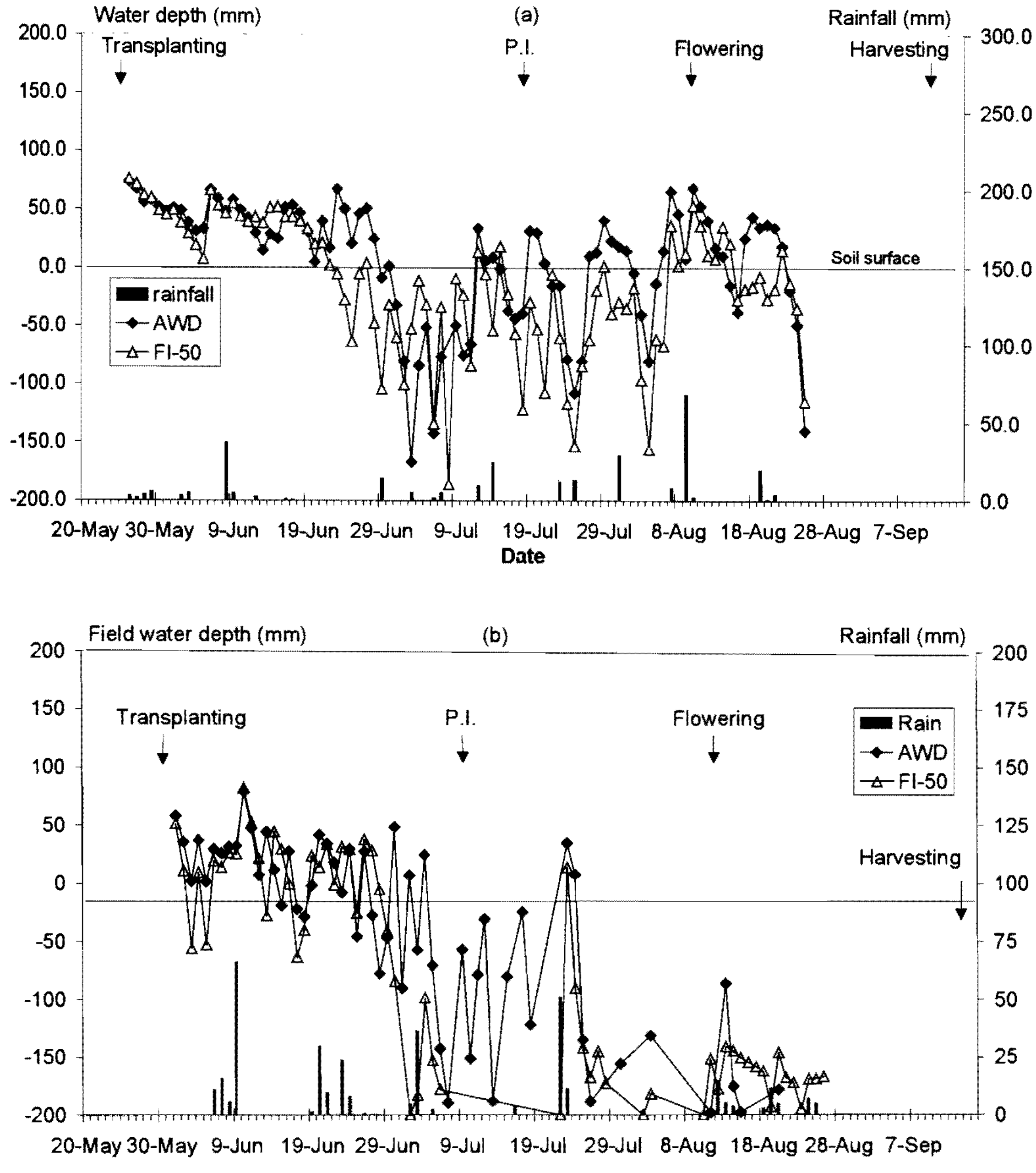


Fig. 2. Mean field-water depths in Tuanlin in (a) 2001 and (b) 2002. AWD = alternate wetting and drying, FI-50 = flush irrigation when soil water potential reaches –50 kPa, PI = panicle initiation.

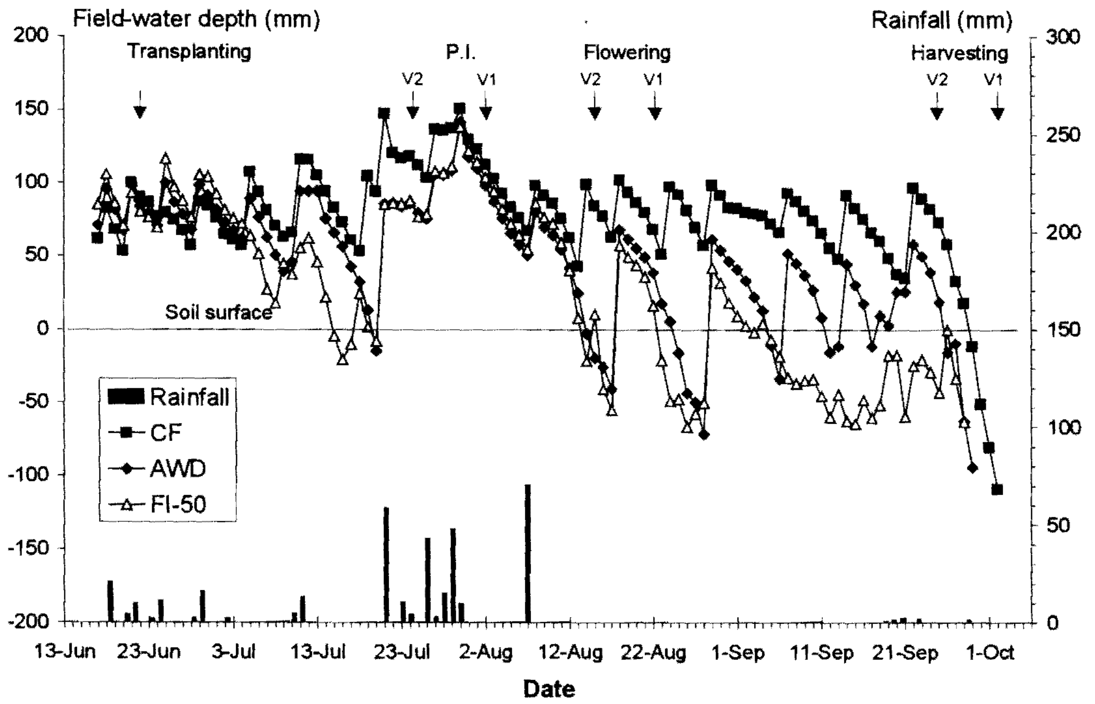


Fig. 3. Mean field-water depths in Huibei, 2001. CF = continuous flooding, AWD = alternate wetting and drying, FI-50 = flush irrigation when soil water potential reaches –50 kPa, PI = panicle initiation, V1 = inbred rice variety, and V2 =

3.3 Grain yield

In Tuanlin, the average grain yield in 2001 in hybrid rice treatments (from 4.9 to 9.5 tons ha^{-1}) was significantly higher than that of the aerobic rice variety (from 0.29 to 1.6 t ha^{-1}, Fig. 4a). The very low yields of aerobic rice variety were due to heavy stem-borer infestation at the post anthesis stage of the crop (data not shown). Due to their pest-induced low values, yields of aerobic rice in Tuanlin 2001 will be excluded from other data analysis in this paper. In 2002, hybrid rice (from 5.6 to 7.1 t ha^{-1}) likewise yielded significantly higher than inbred rice (from 1.4 to 2.1 t ha^{-1}). Low yields in aerobic variety in 2002 were attributed to high spikelet sterility (data not shown).

In 2001-location, the yields in plots with nitrogen were significantly higher ($P < 0.01$) than in plots without nitrogen application. This conforms to previous findings by Cabangon et al. (2001). In 2002-location, however, there was no significant difference in grain yields between the two N-treatments. This could be due to high indigenous N-supply in the 2002-location (Table 1).

Table 3: Number of days with standing water in the field. Tuanlin, 2001 and 2002.

Treatment	2001*	2002*
AWD	49 ± 4	24 ± 2
Flush Irrigation at –50 kPa	32 ± 4	17 ± 2
Partially Rainfed	33 ± 5	17 ± 3

* Number of samples =12 (from 2 varieties, 2 N treatments and 3 reps)

Table 4. Number of days with standing water in the field during the crop season and transplanting recovery period in Huibei, Kaifeng, 2001 and 2002. In 2002, the standing water in the field lasted only a few hours after irrigation; the number of days with standing water equals the number of irrigation events.

Treatment	Days with standing water			
	Crop season		Transplanting recovery period	
	V1[a]	V2[b]	V1	V2
2001[c]				
Continuous Flooding	93 ± 2	92 ± 0	10 ± 0	10 ± 0
Alternate wetting and drying	71 ± 6	65 ± 9	10 ± 0	10 ± 0
Flush irrigation at-50 kPa	44 ± 15	37 ± 15	10 ± 0	10 ± 0
2002[d]				
Flush irrigation at-10 kPa	44 ± 1	40 ± 1	14 ± 1	17 ± 1
Flush irrigation at-30 kPa	24 ± 1	27 ± 1	13 ± 1	17 ± 1
Flush irrigation at-70 kPa	21 ± 1	22 ± 1	14 ± 1	17 ± 0
Rainfed	16 ± 1	20 ± 1	14 ± 0	17 ± 1

[a]V1 = inbred rice   [c]Number of samples = 3 (from three replicates)

[b]V2 = aerobic rice   [d]Number of samples = 4 (from four replicates)

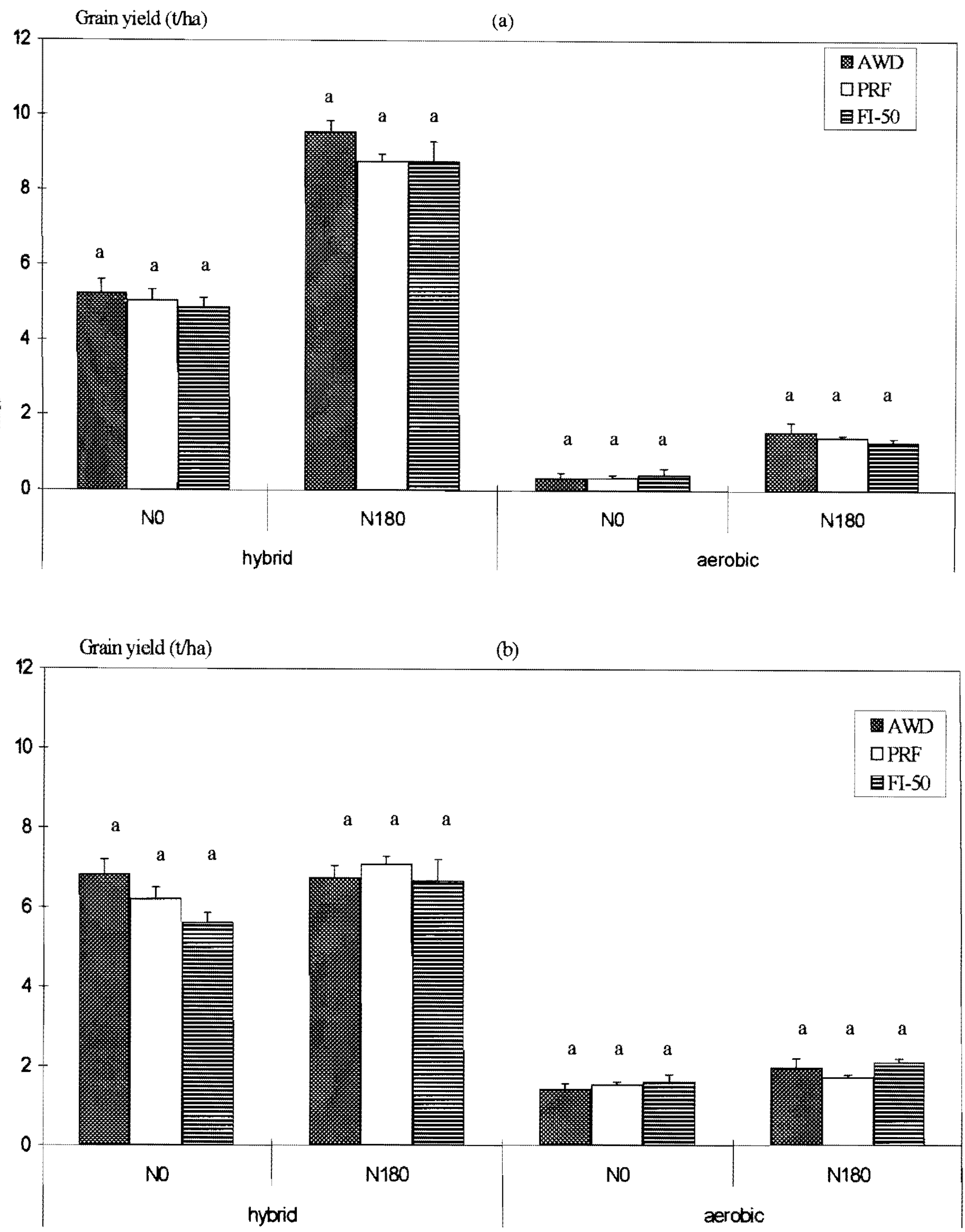


Fig. 4. Mean grain yields of hybrid and aerobic varieties in Tuanlin in (a) 2001-location and (b) 2002-location. AWD = alternate wetting and drying, PRF = Partially rainfed, FI-50 = flush irrigation at –50 kPa. Columns with the same letters are not significantly

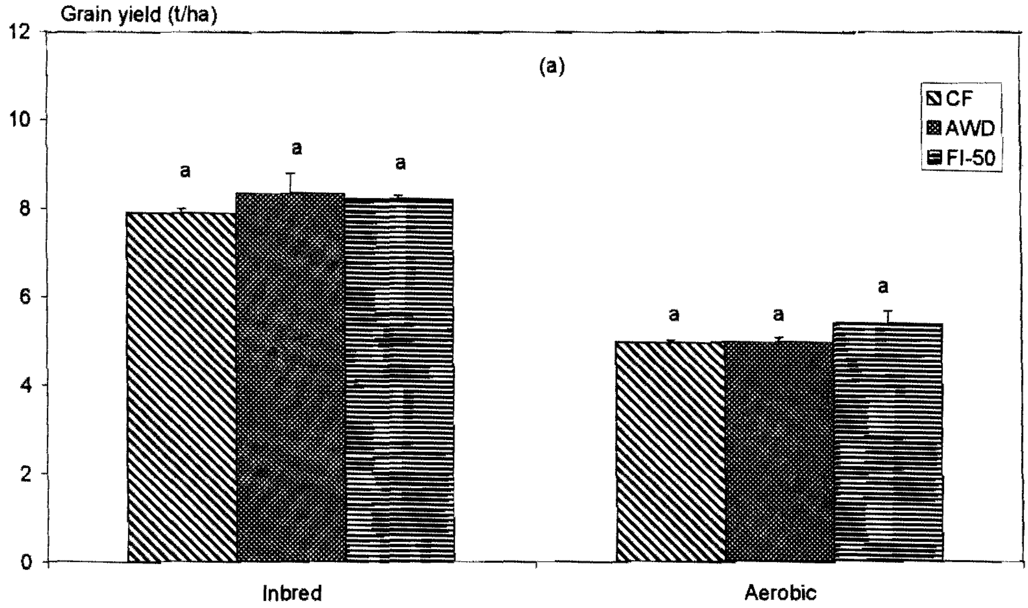
Among the water treatments AWD had the highest average grain yields, but did not differ significantly compared to PRF and FI-50 at the 5% level (Fig. 4a).

In Huibei, the average grain yield ranged from 5.0 to 8.3 t ha^{-1} (Figure 5a) in 2001. The local inbred rice variety had significantly higher yields ($P < 0.01$) compared with the aerobic variety. Likewise in 2002, the local inbred variety had significantly higher yields than the aerobic variety as shown in Fig. 5b. Lower yields of aerobic variety may be attributed to its lower tillering ability and a shorter duration (103-107 d versus 115-119 d) compared with the inbred variety.

In Huibei, there was no significant difference in yields among the water treatments in both rice varieties in 2001 (Fig. 5a). In 2002 yields tended to increase with the number of days with standing water (Fig. 5b and Table 4). In the inbred variety, FI-10 and FI-30 had significantly higher yields compared to FI-70, which was significantly higher than PRF. In the aerobic variety, FI-10 had higher yields than other treatments, but significantly ($P < 0.05$) only when compared with FI-70 and PRF. There was no significant difference in yields among FI-30, FI-70 and PRF.

The yield difference between the best and the worst treatments in 2002 experiment for inbred variety was about 46% of the lowest. Corresponding value for aerobic variety was 17%. This implies that inbred rice was more susceptible to drought than aerobic variety. Despite the higher sunshine hours, the inbred variety in the best treatment in 2002 (FI-10) yielded less (7 vs. 8 tons ha^{-1}) than the best treatment in 2001 (CF), confirming that a slight water stress might result in yield penalty in the inbred variety.

The different response in rice yields to water treatments in two years at the two sites maybe attributed to different groundwater depths. The lack of a significant difference in 2001 and in 2002 in Tuanlin was due to the high water table conditions (Fig. 1), which supplied water to the rootzone during days without standing water in the AWD, FI-50, and PRF treatments. The deep water table in Huibei in 2002 allowed different water treatments to impose different stress levels on the rice plants.



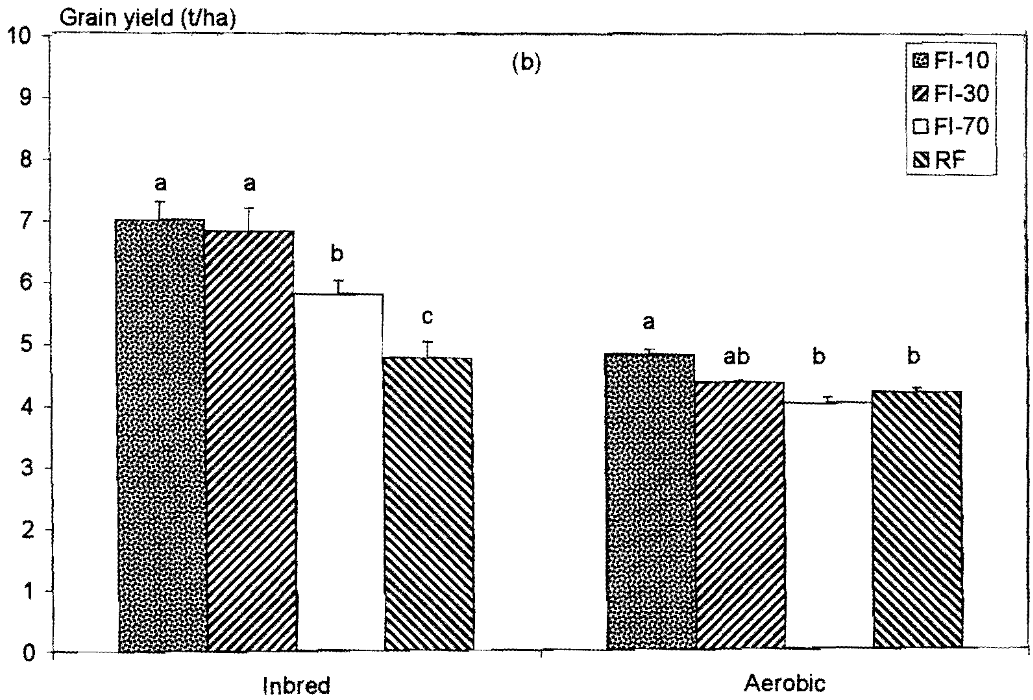


Fig. 5. Mean grain yields of inbred and aerobic varieties in Huibei in (a) 2001 and (b) 2002. CF=continuous flooding, AWD = alternate wetting and drying, PRF = rainfed, FI-10 = flush irrigation at –10 kPa, FI-30 = flush irrigation at –30 kPa, FI-50 = flush irrigation at –50 kPa, and FI-70= flush irrigation at –70 kPa. Columns with the same

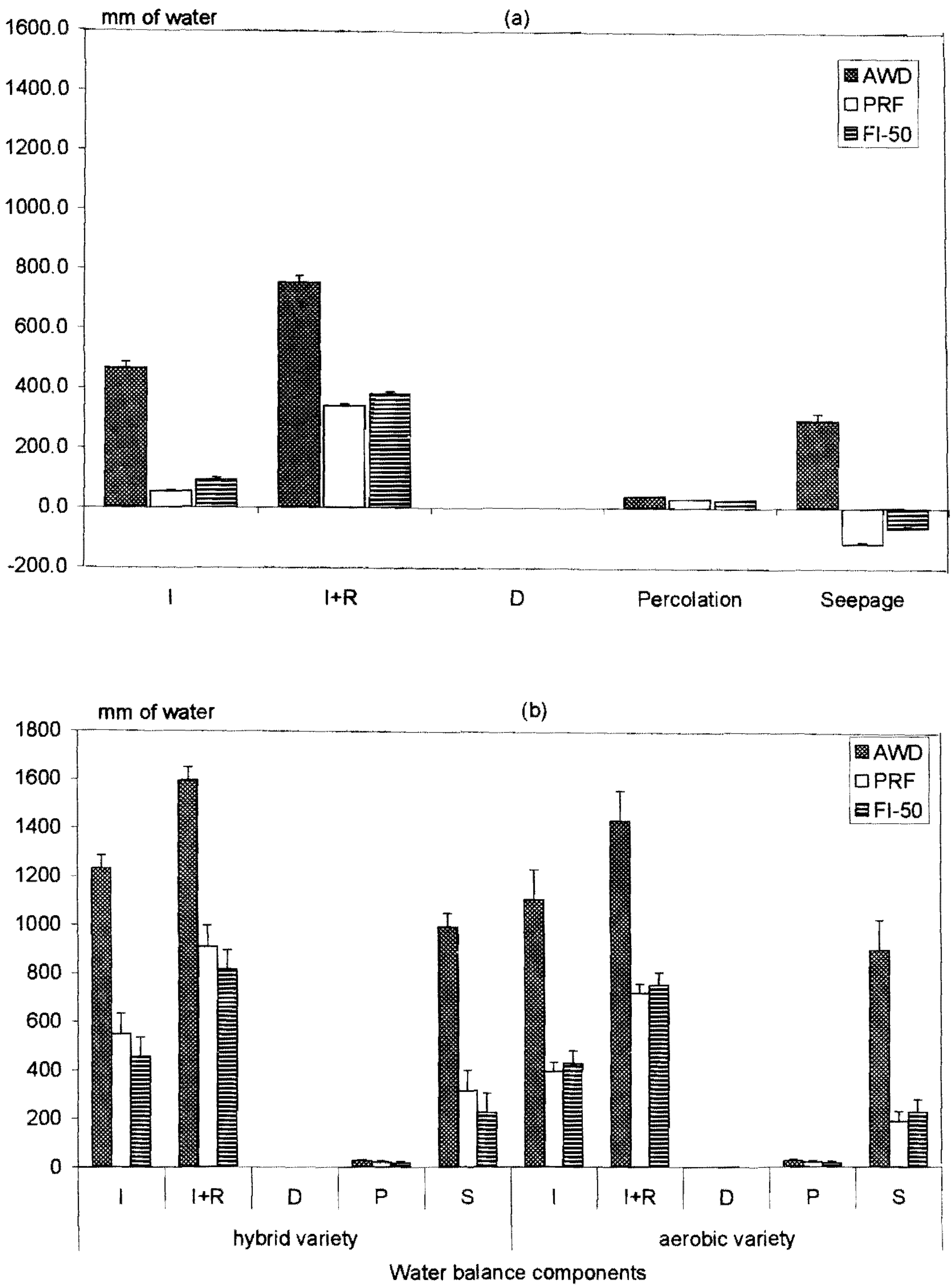


Fig. 6. Irrigation (I), total water input (I+R), drainage (D), and seepage (S) and percolation (P) during the crop season (from transplanting to harvest) in Tuanlin, in (a) 2001, for hybrid variety only; and in (b) 2002. AWD = alternate wetting and drying, PRF = rainfed. FI-50 = flush irrigation at –50 kPa. Values are average of two N

3.4 Water Balance

Figure 6 shows the water balance components for the different water treatments from transplanting to harvest in two years in Tuanlin. In 2001 (for plots with hybrid rice only), the total water input (rainfall + irrigation) ranged from 320 to 750 mm, of which there was 297 mm of rainfall (Fig. 6a). In 2002, the total water input ranged from 800 to 1600 mm, and rainfall was 350 mm (Fig. 6b). The total water input and irrigation in AWD treatment were significantly higher than those in FI-50 and PRF treatments. There was no drainage in neither year.

The average percolation rate in 2001-location was 0.7 mm d^{-1}, and in 2002-location 1.4 mm d^{-1}. Summing over the whole season, percolation was 35 - 40 mm in AWD and 25 - 30 mm in the other treatments (Fig. 6a and 6b). Lower percolation rate in the 2001-location was attributed the shallower groundwater table (Fig. 1a) and heavier soil (Table 1) than the 2002-location. Despite the higher percolation rate in 2002, the seasonal percolation was similar in both years. This was due to the lower number of days with standing water in 2002 (Table 3). Water balance computation showed that considerable amount of seepage occurred in the AWD in both years (Fig. 6a and 6b). However, there was a net negative seepage in the PRF and FI-50 treatments in 2001 (Fig. 6a), indicating that these treatments received seepage water from the surroundings. This occurred because the water level in these treatments was lower than those in the surroundings. In the 2002-location, the calculated seasonal seepage loss was highest in AWD compared to PRF and FI-50. The seasonal seepage in the 2002-location was higher in 2001 due to movement of water to the surrounding drainage ditches.

Figure 7 shows the water balance components for the different water treatments from transplanting to harvest in two years in Huibei. In 2001, water inputs for both varieties were the same since the irrigation input was measured in the main plots. In 2001, the total water input ranged from 570 to 930 mm, of which 354 mm was rainfall (Fig. 7a). The differences in irrigation and total water inputs were statistically significant among all three water treatments ($P < 0.01$), with CF having the highest values and FI the lowest. The daily percolation rates ranged from 0.2 to 1.4 mm d^{-1}, averaging 0.7 mm d^{-1}. The low percolation rate, despite the light textured soil of the site, was attributed to the shallow groundwater table (Fig. 1b). Summed over the whole season, percolation loss was about 60 mm, with no statistical difference at the 5% level among the water treatments. The mean seasonal surface drainage in CF was significantly higher than in AWD and FI-50, which were able to make more effective use of rainfall than CF treatment. In Huibei, there were net seepage and percolation losses in all treatments. Treatment CF had significantly the highest seepage and FI-50 the lowest (Fig. 7a).

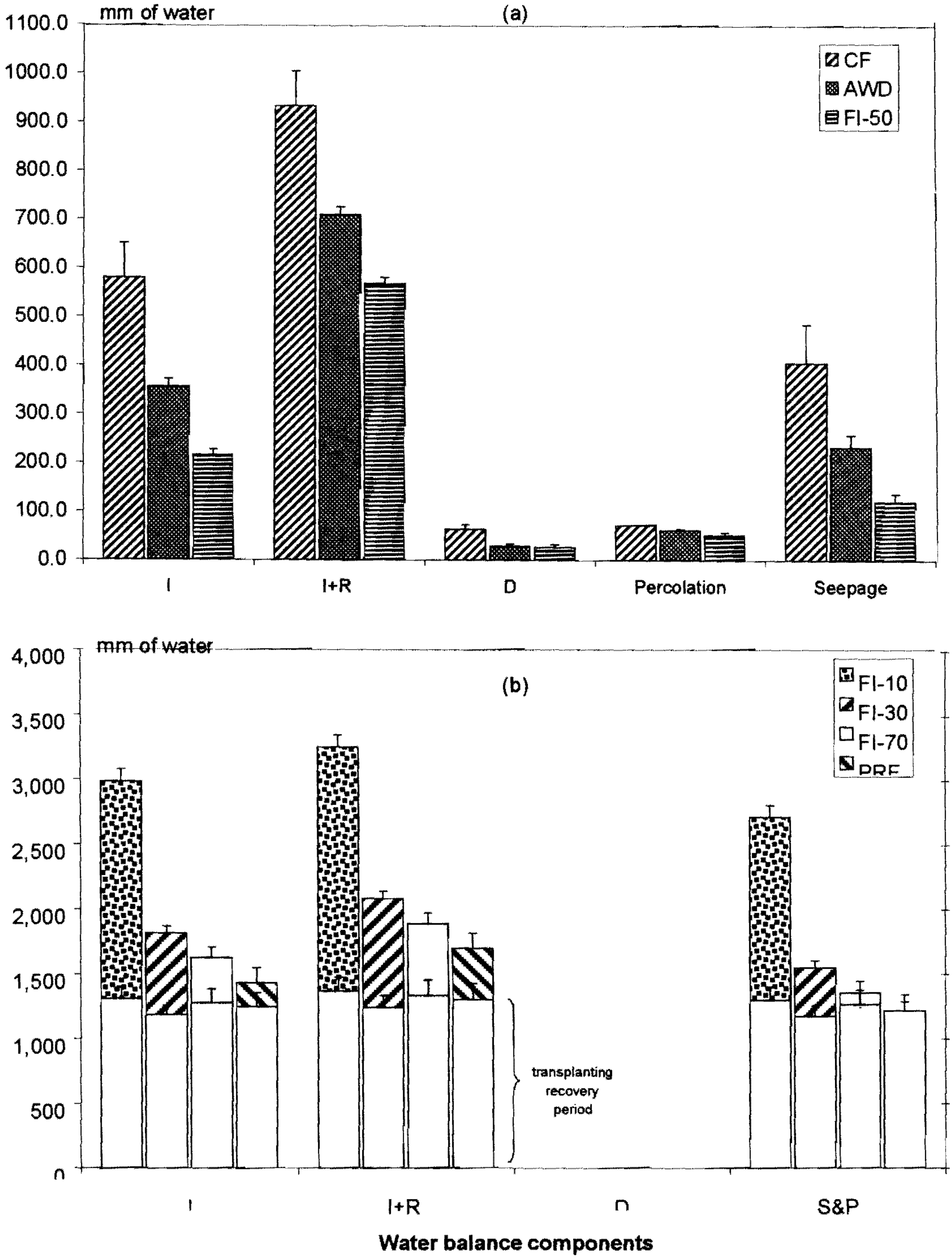


Fig. 7. Irrigation (I), total water input (I + R), drainage (D), and seepage and percolation (S&P) during the crop season (from transplanting to harvest) in Huibei, in (a) 2001 and in (b) 2002. The lower portion of the bars in (b) represents the amount of water during the transplanting recovery period. CF = continuous flooding, AWD = alternate wetting and drying, PRF = rainfed, FI-10 = flush irrigation at –10 kPa, FI-30 = flush irrigation at –30 kPa, FI-50 = flush irrigation at –50 kPa, and FI-70 = flush irrigation at –70 kPa. Data in 2001 are the average of 3 replications and in 2002 of two varieties and four replications.

In 2002, the total water input ranged from 1,008 to 3,338 mm, of which 267 mm was rainfall. The differences in irrigation water inputs among the treatments were statistically significant ($P < 0.05$). Irrigation water input was highest in FI-10, followed by FI-30, FI-70, and RF. A similar level of significance was found in the S&P values. No drainage occurred in 2002 (Fig. 7b) because rainfall was very low during the crop season (Table 1).

The water inputs in 2002 were much higher than in 2001. This was attributed to a much higher S&P, because of lighter soil and a deeper water table, in 2002 than in 2001 (Fig. 7a vs. Fig. 7b). Most (about 1,300 mm) of the S&P in 2002 occurred during the transplanting recovery period, when irrigation has to be applied daily to keep the field flooded (though only a part of the day) to help plants recover from the transplanting shock. This period was longer in the aerobic rice variety than in the inbred rice variety (17 vs. 10 d, Table 2), indicating that the former suffered more severe transplanting shock than the latter. The irrigation amount supplied during transplanting recovery to the aerobic variety was higher than that supplied to the inbred variety.

3.5 Water productivity

3.5.1 Tuanlin

In 2001, the mean water productivity for hybrid rice per unit volume of total water input (WP_{I+R}) ranged from 0.8 to 2.4 kg m^{-3}, and WP_I ranged from 1 to 16 kg m^{-3} (Fig. 8a). High values of WP_I were attributed to the fact that rainfall and capillary rise from shallow water table supplied adequate water for the crop, thus, there is little need for irrigation. Among the three water treatments, PRF had significantly highest water productivities, while AWD had the lowest ones. There was no significant difference in WP_{I+R} between PRF and FI-50 in both N treatments. There was also no significant difference in WP_I between PRF and FI-50 in the N_{180} treatment. However, a significant difference in WP_I was observed in the N_0 treatment. Treatment N_{180} had higher WP_{I+R} compared to N_0 in all water treatments. This implies that application of nitrogen fertilizer is also an essential element in improving water productivity in rice.

In 2002, the mean water productivity, WP_{I+R}, ranged from 0.1 to 0.8 kg m^{-3}, while WP_I ranged from 0.6 to 1.6 kg m^{-3} (Fig. 8b). The WP_{I+R} values are relatively low due to the combination of relatively high water inputs and low yields. The low values of WP_I in aerobic rice were caused by the extremely low yields in these treatments.

3.5.2 Huibei

In 2001, the mean WP_{I+R} ranged from 0.87 to 1.45 kg m^{-3} for inbred rice, and 0.54 to 0.95 kg m^{-3} for aerobic rice. Corresponding values for WP_I were 1.47 to 3.88 kg m^{-3} and 0.92 to 2.56

kg m^{-3} (Fig. 9a). FI had significantly the highest and CF the lowest WP_{I+R} for both varieties. Because of the higher yields of inbred rice(Fig. 5a), (WP_{I+R}) in plots with inbred rice was higher than that with aerobic rice in the same water treatment. The relative trends and differences in water productivity with respect to irrigation were the same as in water productivity with respect to the total water input.

In 2002, the mean WP_{I+R} ranged from 0.15 to 0.34 kg m^{-3}, and WP_I ranged from 0.17 to 0.41 kg m^{-3} (Fig. 9b). The WP_{I+R} values are relatively low compared with previous studies (see Bouman and Tuong 2001 for review data) and are explained by the combination of relatively lower yields (of aerobic rice, Fig. 5b) and extremely high water inputs (Fig. 7b), especially in the FI-10 treatment. Among the four water treatments, FI-10 had the significantly lowest WP_{I+R} and WP_I. The differences among FI-30, FI-70, and PRF were not significant.

4. DISCUSSION AND CONCLUSIONS

The aerobic rice variety HD502 used in our experiments was primarily bred for and tested in, temperate zones of China (Wang Huaqi et al. 2002). In Tuanlin, aerobic rice suffered heavy infestation of stem borer after the flowering (in 2001) and or had high spikelet sterility (2002). Choice of aerobic varieties which are more resistant to stem borer or proper pest management and suitable to that climatic condition may be applied to obtain better yields. Due to different crop durations, flowering of aerobic rice occurred about 12 days after that of the hybrid rice. Heavy stem borer infestation in aerobic rice after flowering could be attributed to pest population build up in late mature crops. Better crop establishment timing to synchronize the flowering of aerobic rice with the surrounding farmer's crops may help reduce the risk of pest infestation.

The relatively high yields (around 5 t ha^{-1}) we obtained in Huibei are an indication that aerobic rice varieties can also be grown in subtropical environments of the north Central China. The lower yield of the aerobic variety compared with that of the inbred variety was related to its shorter duration and lower tillering capacity. On contrast, a shorter duration may have other advantages compensating for the lower yield, such as allowing earlier establishment of a post-rice crop and thereby increasing its yield, and perhaps increasing total system productivity and/or water productivity. Increasing plant density may compensate for the lower tillering capacity of aerobic rice.

Aerobic rice was bred and selected for direct seeding. This could explain the more severe transplanting shock (as reflected by the longer period of transplanting recovery) than with the inbred variety. Transplanting shock can be avoided by establishing the crop by direct-seeding methods. This may further increase the yield of the aerobic rice. More importantly, direct seeding removes the need for maintaining standing water in the field during the transplanting recovery period (of the transplanted rice), which would reduce the amount of irrigation substantially, especially when the soil is permeable and the groundwater is deep. Direct seeding is thus very important for increasing the water productivity of aerobic rice.

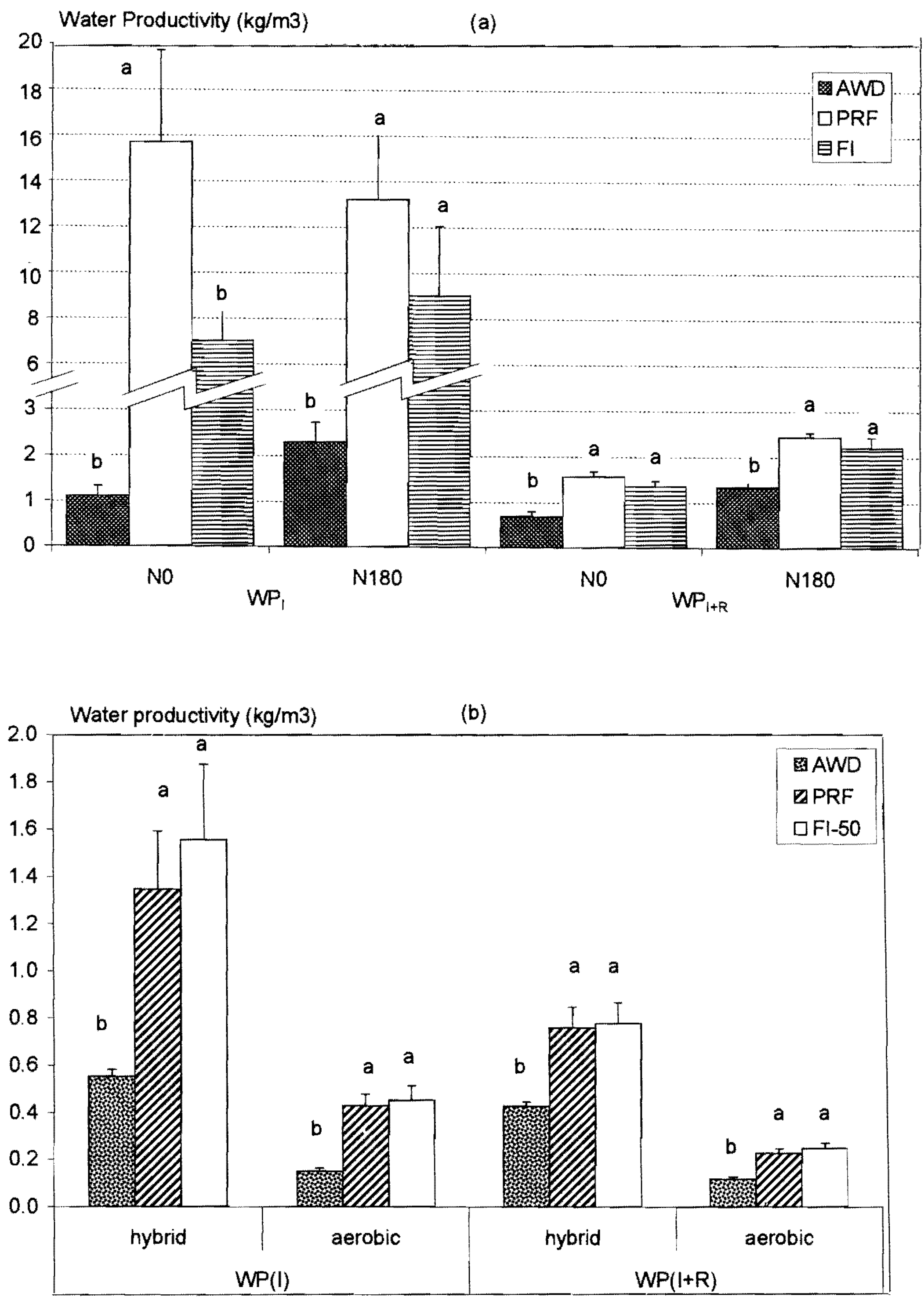
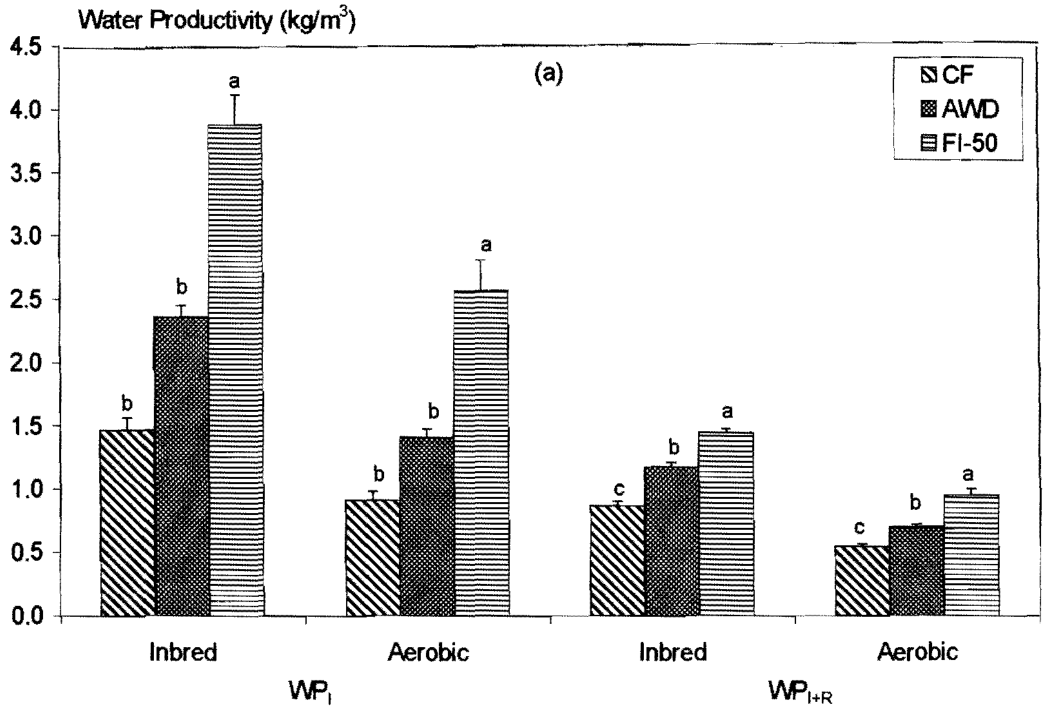


Fig. 8. Water productivities with respect to irrigation (WP_I) & total water input (WP_{I+R}) in different water treatments, nitrogen treatments in Tuanlin (a) 2001 in V1 hybrid variety and in different water and varieities in (b) 2002. AWD = alternate wetting and drying, PRF = rainfed, FI-50 = flush irrigation at −50 kPa, For each nitrogen (2001) and variety (2002), columns with the same letters are not significantly different at the 5% level.



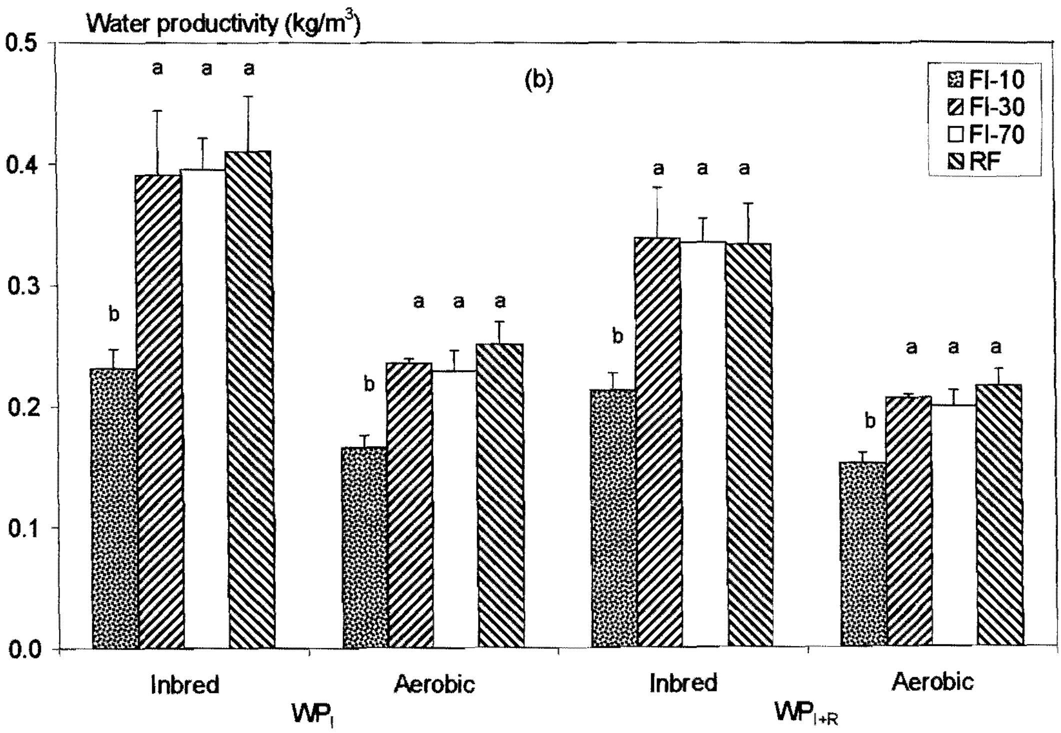


Fig. 9. Water productivities with respect to irrigation (WP_I) & total water input (WP_{I+R}) in different water treatments and varieties in Huibei 2001 (a) and Huibei 2002 (b). CF = continuous flooding, AWD = alternate wetting and drying, PRF = rainfed, FI-10 = flush irrigation at –10 kPa, FI-30 = flush irrigation at –30 kPa, FI-50 = flush irrigation at –50 kPa, and FI-70 = flush irrigation at –70 kPa. For each variety, columns with the same letters are not significantly different at the 5% level.

Water-saving irrigation, especially flush irrigation and partially rainfed systems, can significantly reduce the amount of irrigation compared with farmers' practices, without affecting rice yield if the soil water potential is not allowed to drop below –30 kPa. This implies that there is a possibility for irrigation system managers to reduce the amount of water diverted to rice at the study sites. These findings and their implications, however, are site-specific and care must be taken in extrapolation. Our results were obtained in relatively small subplots in farmers' fields which allowed us to keep irrigation time short and the irrigation application efficient. In larger fields, the irrigation time is longer, which may result in larger seepage and deep-percolation losses. Our results also confirmed that yield responses to irrigation management are highly dependent on groundwater depth. Data on the effect of irrigation management were useful only when groundwater depth and soil conditions were specified. More study is needed on the interaction between irrigation and groundwater table depths before recommendations for the large-scale application of water-saving irrigation techniques can be made. Furthermore, seepage from unlined irrigation canals in our study areas may also recharge the groundwater. With the wide-scale adoption of water-saving irrigation techniques, the groundwater tables may go down because of less groundwater recharge from the rice fields and the effect of irrigation management on yield may become more prominent. Systems approaches, using models, may be useful in analyzing the complex interactive effect of groundwater, canal, and irrigation management on rice yield and water productivity.

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REFERENCES

Bouman BAM. 2001. Water-efficient management strategies in rice production. Int. Rice Res Notes 16(2):17-22.

Bouman BAM, Tuong TP. 2001. Field water management to save water and increase its productivity in irrigated rice. Agric. Water Manage. 49:11-30.

Cabangon RJ, Castillo EG, Bao LX, Lu G, Wang GH, Cui YL, Tuong TP, Bouman BAM, Li YH, Chen CD, Wang JZ. 2001. Impact of alternate wetting and drying irrigation on rice growth and resource-use efficiency. In: Barker R, Loeve R, Li YH, Tuong TP, editors. 2001. Water-saving irrigation for rice. Proceedings of an International Workshop held in Wuhan, China, 13-25 March 2001. Colombo (Sri Lanka): International Water Management Institute. p 55-80.

De Datta SK, Abilay WP, Kalwar GN. 1973. Water stress effects in flooded tropical rice. In: Water management in Philippine irrigation systems: research and operations. Los Baños (Philippines): International Rice Research Institute. p 19-36.

Li YH. 2001. Research and practice of water-saving irrigation for rice in China. In: Barker R, Li YH, Tuong TP, editors. Water-saving irrigation for rice. Proceedings of an International Workshop held in Wuhan, China, 23-25 March 2001. Colombo (Sri Lanka): International Water Management Institute. p 135-144.

Mao Zhi. 1993. Environmental impact of water-saving irrigation for rice. Proceedings of Environmentally Sound Water Resource Utilisation, AIT Bangkok, Thailand, 8-11 Nov. 1993. p 143-148.

McCauley GN. 1990. Sprinkler vs flood-irrigation in traditional rice production regions of southeast Texas. Agron. J. 82:677-683.

Tabbal DF, Bouman BAM, Bhuiyan SI, Sibayan EB, Sattar MA. 2002. On-farm strategies for reducing water input in irrigated rice: case studies in the Philippines. Agric. Water Manage. 56(2):93-112.

Tuong TP, Bouman BAM. 2002. Rice production in water-scarce environments. To be published in proceedings of the Water Productivity Workshop, 12-14 November 2001, International Water Management Institute, Sri Lanka.

Wang Huaqi, Bouman BAM, Zhao D, Moya P, Wang C. 2002. Aerobic rice in North China: opportunities and challenges. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK, editors. 2003. Water-wise rice production. Los Baños

(Philippines): International Rice Research Institute. p 143-154.

Westcott MP, Vines KW. 1986. A comparison of sprinkler and flood irrigation for rice. Agron. J. 78:637-640.

Xu Zhifang. 1982. Irrigation of rice in China. Wuhan, Department of Irrigation and Drainage Engineering, Wuhan Institute of Hydraulic and Electric Engineering, Wuhan, China.

Yang Xiaguang, Wang H, Wang Z, Zhao J, Chan B, Bouman BAM. 2002. Yield of aerobic rice (Han Dao) under different water regimes in North China. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK, editors. 2002. Water-wise rice production. Los Baños (Philippines): International Rice Research Institute. p 155-163