Chapter 4

Impact of Alternate Wetting and Drying Irrigation on Rice Growth and Resource-Use Efficiency

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Abstract

The objective of this study was to quantify the impact of alternate wetting and drying irrigation (AWD) and timing of N-fertilizer application on rice growth, water input, water productivity and fertilizer-use efficiency. The experiment was carried out in 1999 and 2000 in Jinhua, Zhejiang Province and in Tuanlin (TL), Hubei Province, following a split-plot design. The main plots were 2 water treatments (W_1 = AWD irrigation, W_2 = continuous flooding). The subplots consisted of four N-application treatments (F_0 = control, no N fertilizer; F_1 = 2 splits, as farmers practice; F_2 = 4 splits and F_3 = 5 or 6 splits depending on the season). The total N input in all seasons was 150 and 180 kg N ha^{-1} in Jinhua and TL, respectively.

Grain yields varied from 3.2 to 5.8 tons ha^{-1} in Jinhua, while higher grain yields were obtained in TL (4.5 to 9.1 tons ha^{-}). In both sites, there were no significant water-nutrient interactions on grain yields, biomass and N uptakes. In most cases, continuous flooding gave 1–7% higher yields than AWD, but the reverse was true in TL for 2000. However, the difference in yield was not statistically significant at 5% level. The AWD reduces irrigation water compared to continuous flooding. The differences were statistically significant only in 2000 when rainfall was low and evaporation demand was high. Water productivity in terms of irrigation water was about 5–35% higher under AWD than in continuous flooding but differences were significant only in the year 2000.

Increasing the number of splits to 4–6 times (i.e., F_1–F_3) increased the total N uptake, but not grain yield and biomass compared to farmers' practices of 2 splits. This may reflect the inability of the studied rice varieties to convert N taken up into grain.

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We concluded that under the experimental conditions, AWD irrigation did not reduce rice yield but increased the water productivity. This increase may become more pronounced in drier conditions. The AWD did not require a different N-fertilizer management from continuous flooding.

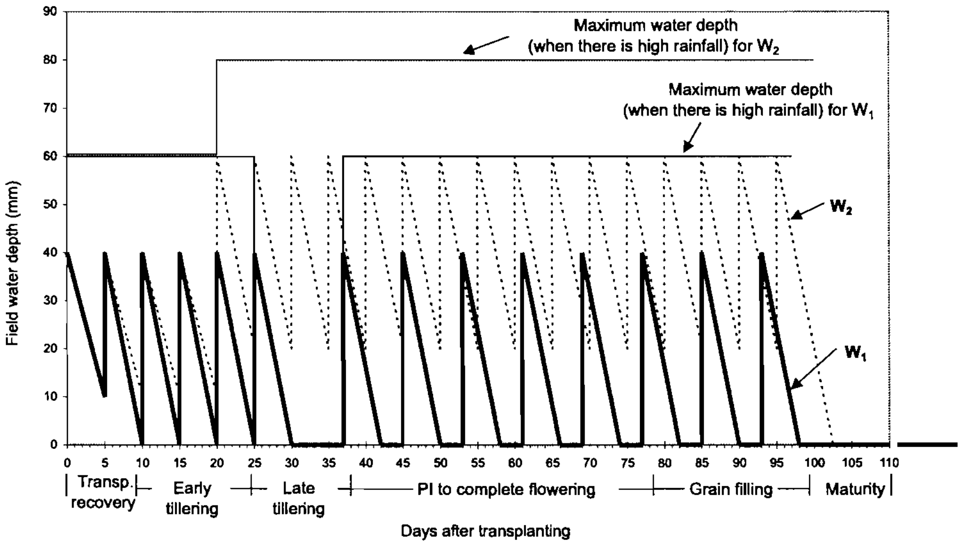
Introduction

Irrigation has played a critical role in the increase of rice production in China. Irrigated rice produces 96% of the annual rice production of 130.6 million tons in 1990 (Rosegrant et al. 1995). Despite having the most intensive rice irrigation in the world, per capita freshwater availability in China is among the lowest in Asia. Rapid industrialization and urbanization will further divert water from agricultural use. The need for "more rice with less water" is crucial for food security and is more urgent in China than in many other Asian countries.

Recognizing the severity of the situation, the government and the people of the P. R. China have already pioneered various water-saving irrigation (WSI) technologies to achieve more water-efficient irrigation for rice-based systems. One of the most commonly practiced WSI techniques is AWD irrigation. This irrigation method is characterized by a) a mid-season drainage during the late tillering stage of the crop and b) periodic soil drying of 2–4 days in between irrigation events from panicle initiation (PI) on to harvest (figure 1). In the mid-season drainage, the soil is dried out for 10–15 days, depending on the weather condition until some fine cracks appear at the soil surface (Mao Zhi et al. 2000), Xu (1982), Wei and Song (1989) and Mao Zhi (1993a) reported that mid-season drainage and intermittent drying of the soil improved rice yield compared to the traditional irrigation practices with continuous flooding. In fact, the superiority of the AWD irrigation in terms of yield has been reported as one of the main reasons for farmers' acceptance of the new technology. A combination of reduced water input and increased yield resulted in substantial increases in water productivity with respect to irrigation water. The increase in yield under AWD irrigation in China substantially differs from the results reported elsewhere (e.g., Mishra et al. 1990; Tabbal et al. 1992; Bouman and Tuong 2001). Most of the Chinese literature attributes the increase in yield by AWD irrigation to the improvement of the microenvironment of the root zone. There is, however, no scientific evidence to support this reasoning. One possible hypothesis is that, compared to inbred rice, the hybrid rice varieties used in China are more drought-resistant and make better use of nitrogen fertilizer in the form of nitrate (as a result of the nitrification process taking place during the drying periods of AWD irrigation).

There is also evidence that rice cultivation with AWD irrigation has very low fertilizer-use efficiency. Wang et al. (1998) reported that the N recovery efficiency in China is only about 29% in early rice and 5% in late rice in Jinhua, Zhejiang Province. High nitrogen losses could be due to a combination of the present fertilization practice of applying nearly all the fertilizers within 10 days of transplanting, the AWD irrigation practices with the mid-season drainage and the subsequent wet and dry cycles in the later growth stages. Wang et al. (1997) suggested that the present AWD irrigation techniques and N-application practices in China present an enormous challenge for improving N use efficiency.

Figure 1. Designed field water depths in alternate wetting and drying (W_1) and continuously flooded (w_2) in 1999 and 2000, Jinhua, Zhejiang Province and Tuanlin, Hubei Province, P. R. China.



The authors suggested that the techniques have also raised environmental concern. Systematic research on the efficiency of fertilizer use under different water management techniques has not been carried out in China. We hypothesized that applying N in more splits to better synchronize the N-application and water status in AWD irrigation could increase the efficiency of fertilizer use and water productivity.

This study was conducted with the general objective of quantifying the impact of AWD irrigation practices on rice growth and resource-use efficiencies, so as to identify the optimal combination of water and N-fertilizer management. The specific objectives of the study were to quantify rice growth and yield as affected by water management and fertilizer treatments, to compare the amount of water diverted to rice fields and water productivity under AWD and under continuous flooding, and to quantify the recovery and agronomic efficiency of applied N, P and K as affected by fertilizers and the water regime.

Materials and Methods

Experimental Site

The experiments were conducted in 1999 and 2000 at two sites: Jinhua, Zhejiang Province, and TL, Hubei Province, P. R. China. In Jinhua, the experiments were conducted during the early rice (ER) season (March–July) and the late rice (LR) season (June–October). In TL, the experiment was carried out during the mid-season rice crop from May to September. The 20-cm topsoil layer in Jinhua was silt loam and in TL it was clay loam with other characteristics shown in table 1.

Table 1. Soil characteristics of the 20-cm layer, Jinhua and Tuanlin, 1999–2000.

	Jinhua, Zhejiang Province	TL, Hubei Province
Soil type	Silt loam	Clay loam
pH (1:1 H20)	4.7	6.5
Organic carbon (%)	2.03	1.03
Available N (mg kg^{-1})	178	5.8
CEC (cmol kg^{-1})	7.8	20.6

Note: CEC=Cation Exchange Capacity.

Experimental Design and Cultural Practices

The experiments were conducted in a split-plot design with three replications. In TL, a fourth replication was added in 2000. The main plots had two water treatments: (W_1) = AWD and (W_2) = continuous flooding throughout the entire duration of crop growth. The designed water levels in the experiment are shown in figure 1. The subplots consisted of 4-N application timings:

- F_0 = No N application. However, in TL 1999, due to an experimental error, the whole dose of N was applied as basal. Therefore, we indicate the 1999– "control" as F_0*.
- F_1 = Farmers' practice of two applications. 50% of total N was applied one day before transplanting, and 50% 10 days after transplanting (DAT),
- F_2 = Four applications. 30% of total N as basal, 30% at 10 DAT, 30% at PI and 10% at heading.
- F_3 = N-application timings were adjusted to reduce the amount of fertilizer applied at the beginning of the crop. In 1999, this treatment consisted of six applications in both sites: 25% of total N as basal, 25% at 10 DAT, 20% at PI, 10% just before heading, 10% after heading and 10% after complete flowering. In 2000, due to the objection of farmers (owners of the experimental fields) that the 6-split application was too laborious, F_3 was modified to 4-split applications in the early and mid-season rice crops (17% of total N as basal, 20% at 16 DAT, 27% at mid-tillering stage, and 36% at PI), and 5-split application in late-season rice crop (10% as basal, 17% at 16 DAT, 27% at mid-tillering stage, 36% at PI, and 10% at heading).

Nitrogen was applied as urea at the rate of 150 kg N ha^{-1} in Jinhua, and 180 kg N ha^{-1} in TL. Other fertilizers at both sites were 25 kg P ha^{-1} (single superphosphate), and 70 kg K ha^{-1} (KCl) applied and incorporated into individual plots as basal dressing.

All varieties used were hybrid rice.

The subplot area varied from 90 to 200 m^2. All main plots were surrounded by consolidated bunds, equipped with plastic sheets installed to a depth of 0.25 m. Varieties used in Jinhua were V402 (1999) and Xieyou 46 (2000), and in TL, 2you 501 (1999) and 2you 725 (2000). All varieties used were hybrid rice.

Prior to land preparation, weeds were cut and removed from the field. All plots were hoed manually twice across the plots to a depth of 30 cm. The soil was submerged for one week before harrowing and final leveling. Fertilizers for basal dressing were then incorporated one day before transplanting. Seedlings were grown in a wet bed for approximately 32 days and 45 days in Jinhua and TL, respectively, and transplanting was done at two plants per hill with a spacing of 20 cm x 20 cm.

Complete pest control was carried out in all plots to prevent any interference from weeds, diseases or insects that would hinder full quantitative assessment of water X nutrient interactions.

Soil, Water and Climatic Data Measurements

The water depth was measured daily in 40-cm deep x 20-cm diameter PVC pipes installed in each subplot. The bottom (22 cm) of the pipe was perforated with 1-cm diameter holes at 2-cm intervals. The PVC pipes were installed to a depth of 25 cm below the soil surface. The soil inside the cylinder was dug out to a depth of 25 cm to facilitate measurement of the water table below the ground surface.

Each main plot was irrigated separately. During each irrigation event, the flow rate was monitored at 3-minute intervals by a 20-cm cutthroat flume (Jinhua), V-notch weir (TL, 1999) or current meter (TL, 2000) installed at entry points of each main plot. The volume of water applied during an irrigation event was computed by integrating the flow rate with time. The depth of irrigation water applied was computed by dividing the volume of water applied by the area of the main plot.

After a heavy rain, water depths in the plots may exceed the maximum allowable depths. During such conditions, water was drained to maintain the desired water depth. Drainage depth was computed from the field water depth before and after drainage.

The evapotranspiration was computed from the pan-evaporation with values of the crop factor, K_c obtained from Mao Zhi 1992. The amount of seepage and percolation (S&P) was computed as the difference between inputs (irrigation and rainfall) and outputs (evapotranspiration and drainage). The S&P rate was estimated by dividing the S&P by the number of days with standing water.

In TL, daily rainfall, maximum temperature, minimum temperature, radiation and pan-evaporation were recorded daily from the meteorological station located at the experimental site, and other parameters were obtained from a weather station located about 10 km from the site.

Agronomic Parameters and N Uptake

Phenological development was determined for each subplot at PI, heading, flowering (F) and physiological maturity. Samples for total aboveground biomass and total nutrient uptake were taken from the 12-hill area at 15 DAT, 30 DAT, PI, F, and grain filling (GF). At physiological maturity, rice plants from the designated 12-hill area were cut to ground level for yield-component analysis. At full harvestable maturity, plants from an area of 6 m^2 were taken for yield measurements. Subsamples of straw and grain were analyzed for N, P and K. Plants were sampled and processed using the procedure indicated in the Soil and Plant Sampling Measurements Manual (IRRI 1994). The derived parameters below were calculated using equations that follow them:

Nitrogen harvest index (NHI) = $\frac{GN}{TN}$ (1)

Physiological N use efficiency (PNUE, kg grain/kg N uptake)

$$= \frac{GY \times 0.86}{TN} \quad (2)$$

Agronomic N use efficiency (ANUE, kg grain/kg N applied)

$$= \frac{(GY_F - GY_0) \times 0.86}{N_F} \quad (3)$$

Apparent recovery of applied N (AR, %) = $\frac{(TN_F - TN_0) \times 100}{N_F}$ (4)

where,

Factor 0.86 is used to convert grain yield (GY) with 14% MC to dry-weight basis,
GY_0 is grain yield (in kg ha^{-1}, 14% MC) without N application (N0),
GY_F is grain yield (in kg ha^{-1}, 14% MC) with fertilizer N application (NF),
TN is total N uptake (in kg ha^{-1}),
TN_0 is total plant N uptake without N application (in kg ha^{-1}),
TN_F is total plant N uptake with fertilizer N application (in kg ha^{-1}),
N_F is fertilizer N applied (in kg ha^{-1}), and
GN is grain N uptake (in kg ha^{-1}).

We did not compute ANUE and AR for TL in 1999 because the experiment did not include 0-N treatment.

Results

Climatic Parameters

Rainfall, evaporation and sunshine hours from transplanting to harvest in the experimented seasons are shown in table 2. In Jinhua, seasonal rainfall ranged from 330 to 810 mm and was higher in early rice than in late rice. There was only a slight difference in evaporation between early and late rice seasons in 1999. However, evaporation in late rice in 2000 was 25% lower than in early rice. While the highest sunshine duration occurred in early rice in 2000, corresponding to the highest evaporation, variations in sunshine hours did not correspond to the variations in evaporation in other seasons. This was because evaporation also depends on other factors such as wind speed and humidity. In TL, the 2000 crop received higher rainfall, evaporation and sunshine hours than the 1999 crop.

Table 2. Climatic parameters from transplanting to harvesting for the early and late rice crops in Jinhua, Zhejiang Province and for the single rice crop in Tuanlin, Hubei Province, P. R. China, 1999 and 2000.

Site	Season	Rainfall (mm)	Evaporation (mm)	Sunshine hours	Duration* (days)
Jinhua	1999 early rice	810	344	438	96
Jinhua	1999 late rice	330	335	488	84
Jinhua	2000 early rice	591	436	616	90
Jinhua	2000 late rice	403	320	497	92
TL	1999	377	335	573	110
TL	2000	447	382	686	111

*From transplanting to harvest.

Water Depths

Figures 2 and 3 give the mean water levels for the AWD and the continuously flooded treatments for Jinhua and TL, respectively. The small standard errors of the means in Jinhua indicate that the experiment was able to impose the water treatments uniformly across the replications. It was not always possible however to maintain the same water depths in all replications in TL, reflected by high standard errors of the mean water levels (figure 3). This was because replications 3 and 4 were at a lower position in the toposequence than replications 1 and 2.

There was a clear difference in the water regime of the two water treatments. Flooding was maintained in the continuously flooded treatment, while there were periods without standing water in the AWD treatment. Because of rainfall we could not strictly follow the designed water depths in the AWD scheme (compare figures 2 and 3 with figure 1). For example, the drying during the mid-season drainage at the maximum tillering stage of the late rice crops in Jinhua was only a few days instead of the 10–15 days as in the design. Frequent drying periods could not be imposed in the early rice crop in Jinhua in 1999 and in TL in 2000. The data indicate the difficulty in precisely implementing the designed AWD irrigation in farmers' fields. Depending on the location of the field in the toposequence, farmers may or may not succeed in realizing the drying periods as designed.

Figure 2. Mean ± SE of water depths (N=12, from 4 subplots and 3 replications) in alternate wetting and drying (W_1) and continuous flooding (W_2) in 4 seasons in 1999 and 2000, Jinhua, Zhejiang, P. R. China.

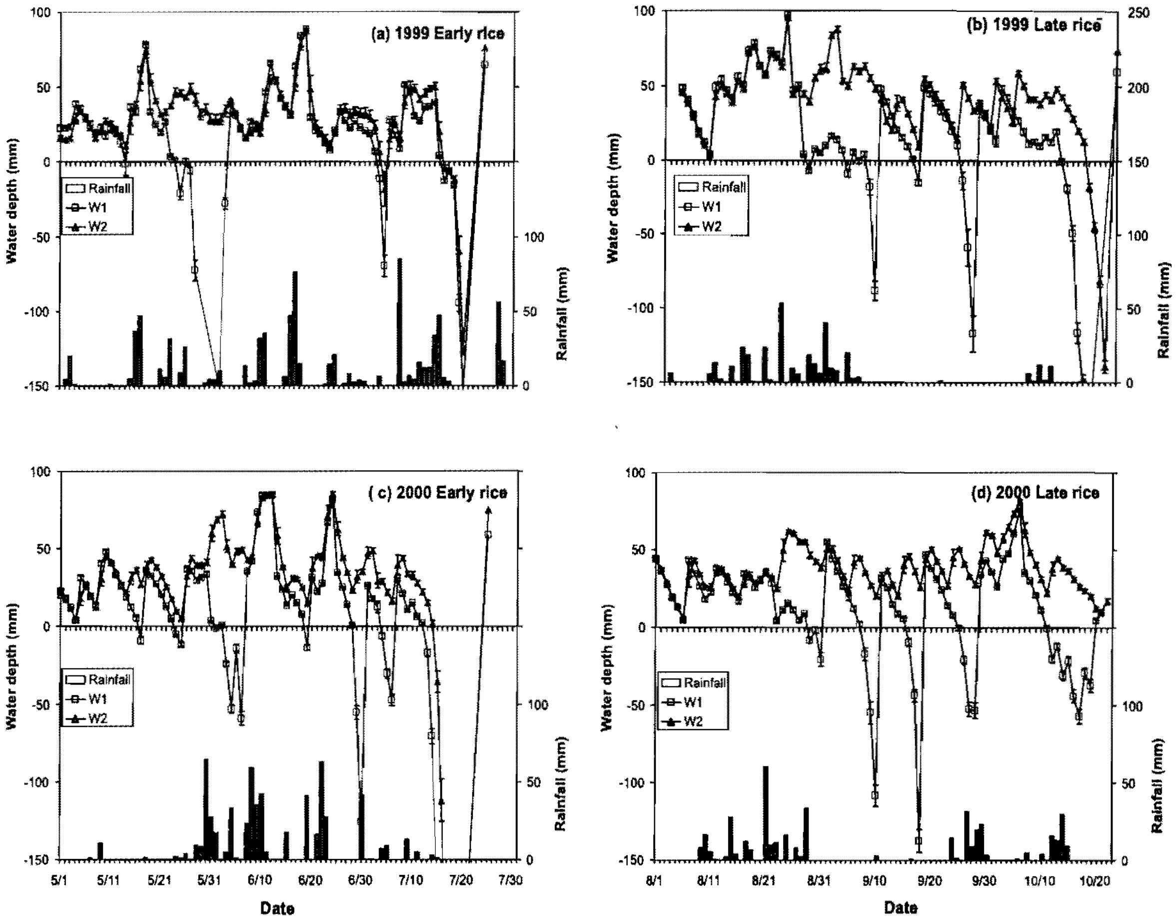
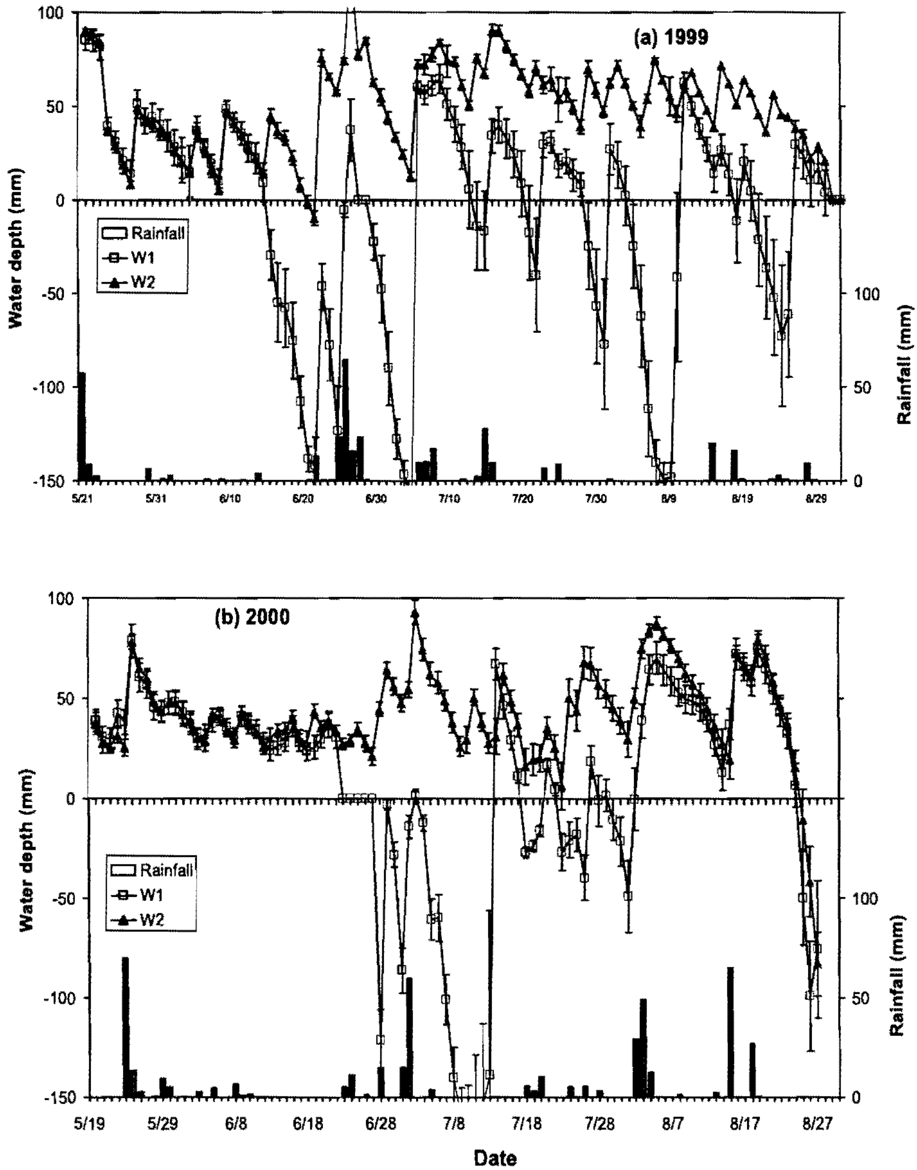


Figure 3. Mean ± SE (N=16, from four subplots and four replications) of water depths in alternate wetting and drying (W1) and continuous flooding (W2) in (a) 1999 all data (b) 1999 without W Rep1(c) 2000 all data and (d) 2000 without W1 Rep1. Tuanlin, Hubei Province, P. R. China.



Grain Yield

Average grain yield ranged from 3.2 to 5.8 t ha^{-1} in Jinhua (figures 4a–d), while higher grain yields of 4.4 to 9.2 t ha^{-1} were obtained in TL (figures 5a–b). Large variation in grain yield within each site was mainly due to yield responses to different treatments. The higher yield in TL was attributed to its longer crop duration compared with Jinhua. On average, grain yield in 2000 was higher than in 1999 in both sites, in accordance with the higher solar radiation in 2000 (table 2).

With regard to grain yield, W x N interaction was not observed in Jinhua in all seasons. In TL, W x N interaction was observed only in the 1999 experiment (tables 3 and 4). In both sites, the fertilizer effect was consistently significant in all seasons. The effect was mainly attributed to the significantly lower yield of the control compared with other fertilized treatments (figures 4 and 5). Among fertilizer splits in Jinhua, F_2 yielded higher than F_1 for most of the time but the difference was significant only in the continuous flooding of the early rice in 2000 (figure 4c). In TL (1999), F_1 gave the lowest yield in AWD but the highest in continuous flooding (figure 5a). In the rice crop of the same site in 2000, there were no observed significant differences among fertilizer split applications (figure 5b).

Figure 4. Effect of water and timing of fertilizer application on grain yield. Jinhua, Zhejiang, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.

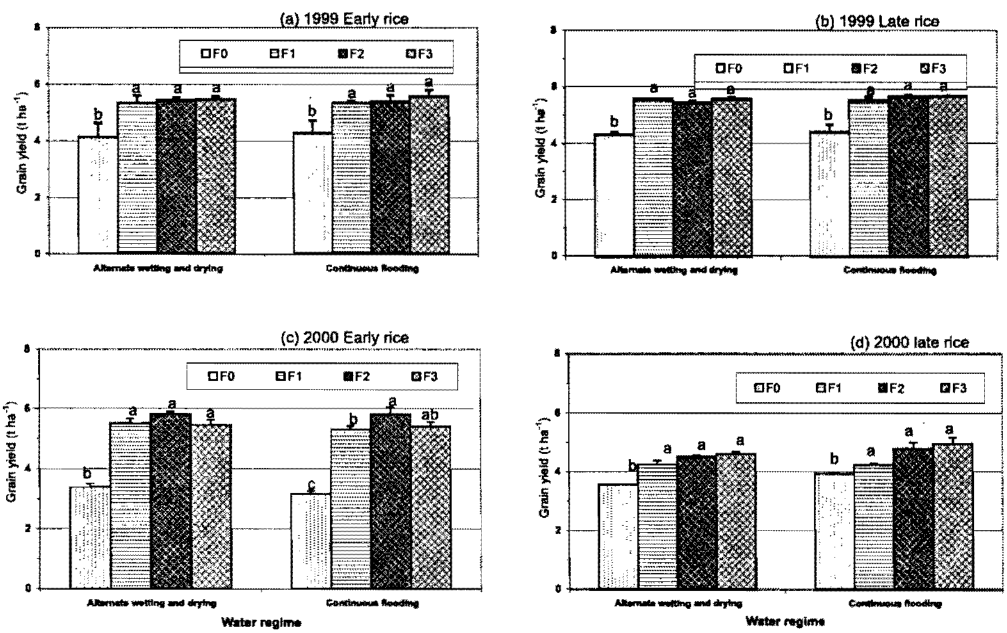
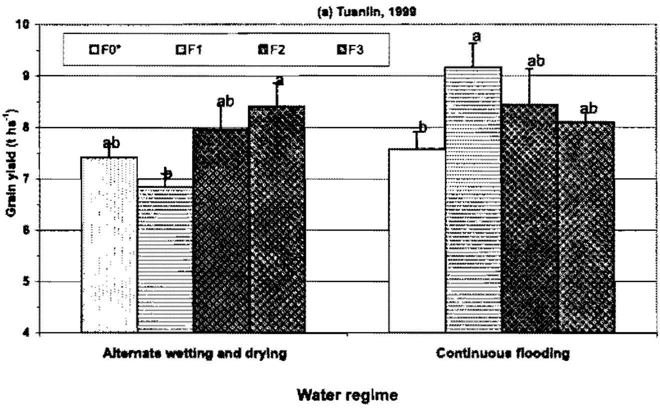
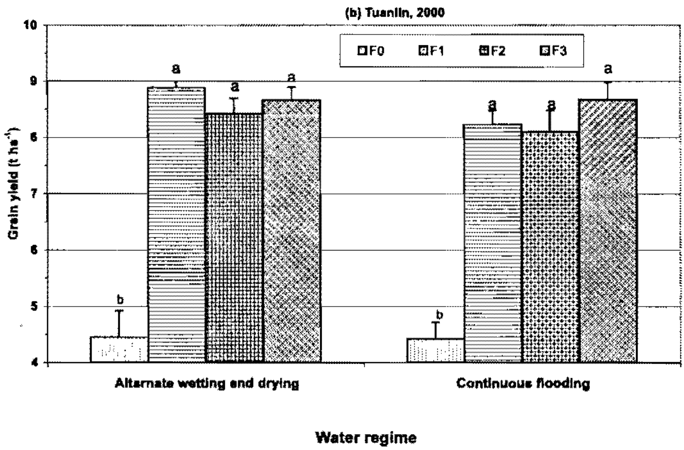


Figure 5. Effect of water and timing of fertilizer application on grain yield. (a) Jinhua, Zhejiang and (b) Tuanlin, Hubei, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.





The difference in grain yield between W_1 and W_2 ranged from 1 to 22%, depending on fertilizer splits and seasons (figures 4 and 5). In most cases, continuous flooding was higher than AWD except for the early rice season in Jinhua in 2000 and the experiment in TL in 2000 where grain yields were higher in the AWD irrigation treatments than in continuously flooded treatments.

Total Dry Matter

The total dry matter production ranged from 4.9 to 9.1 t ha^{-1} in Jinhua (figures 6a to d) and 8.5 to 18.1 t ha^{-1} (figures 7a and b) in TL. The large difference in total dry matter between Jinhua and TL and the variability within a site were due to the same reasons as for the difference in grain yield discussed earlier.

Figure 6. Effect of water and timing of fertilizer application on total dry matter rice, Jinhua, Zhejiang, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.

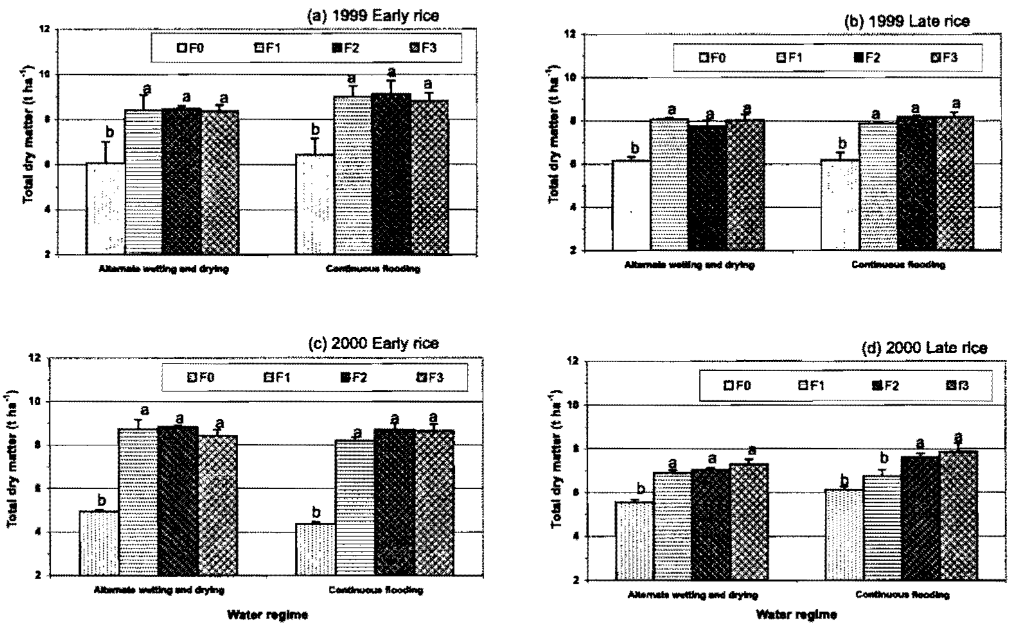
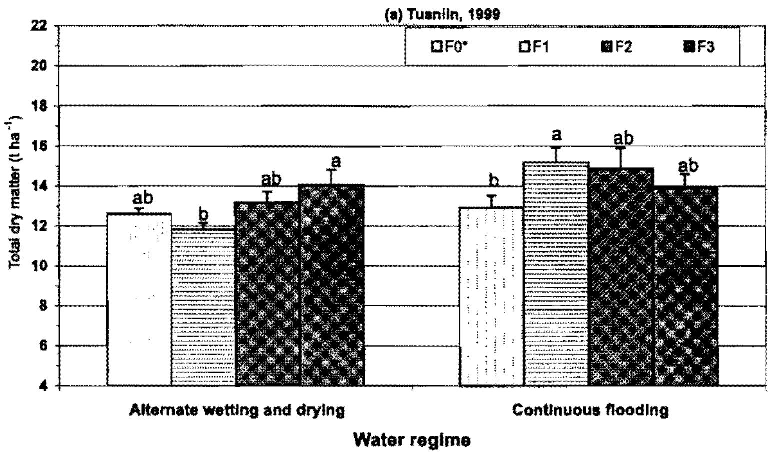
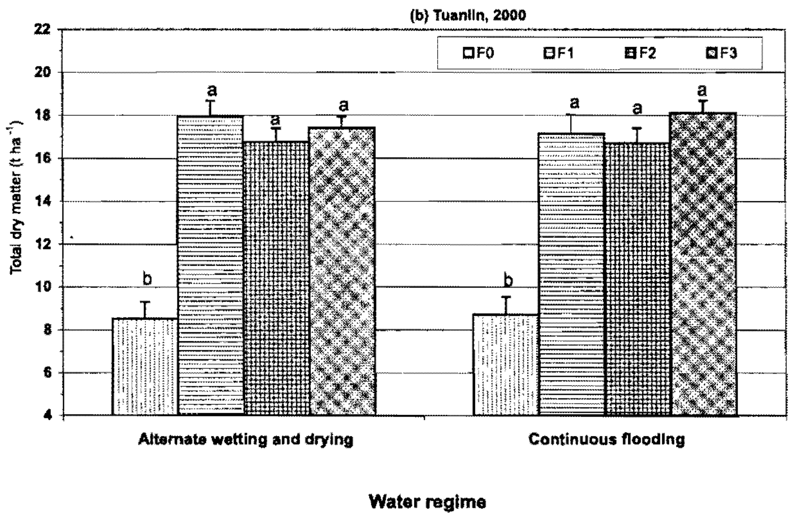


Figure 7. Effects of water and timing of fertilizer application on total dry matter. (a) Jinhua, Zhejiang and (b) Tuanlin, Hubei, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.





There was no observed W x N interaction in the total dry matter (table 3) in both sites. As in grain yield, the fertilizer effect was consistently significant when the control was compared with the mean of fertilizer split N treatments. There was no significant difference in the total dry matter production among F_1, F_2 and F_3 treatments in three out of four seasons in Jinhua (1999 and early rice of 2000) and in both years in TL. In late rice in Jinhua in 2000, however, a significant increase in the total dry matter was observed (figure 6d) in both F_2 and F_3 compared to the farmers' practice of 2-split application.

Table 3. Variability of grain, straw, total dry matter and N uptake as affected by water and timing of fertilizer, Jinhua and TL, 1999–2000.

Factor	Grain yield	Straw yield	Biomass	Total N uptake
		Early rice, Jinhua, 1999		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	**	**
Among F_1, F_2, F_3	ns	ns	ns	**
F_0 v among F_1, F_2, F_3	**	**	**	**
W x N	ns	ns	ns	ns
		Late rice, Jinhua, 1999		
Water regime	ns	ns	**	ns
Fertilizer	**	**	ns	*
Among F_1, F_2, F_3	ns	ns	ns	**
F_0 v among F_1, F_2, F_3	**	**	**	**
W x N	ns	ns	ns	ns
		Early rice, Jinhua, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	ns	**
Among F_1, F_2, F_3	*	ns	ns	**
F_0 v among F_1, F_2, F_3	**	**	**	**
W x N	ns	ns	ns	*
		Late rice, Jinhua, 2000		
Water regime	ns	ns	*	ns
Fertilizer	ns	**	*	ns
Among F_1, F_2, F_3	**	**	ns	*
F_0 v among F_1, F_2, F_3	*	**	-	-
W x N	ns	ns	ns	ns
		Rice season, TL, 1999		
Water regime	ns	ns	ns	ns
Fertilizer	ns	ns	ns	*
Among F_1, F_2, F_3	ns	ns	ns	ns
F_0 v among F_1, F_2, F_3	*	ns	ns	*
W x N	*	ns	ns	ns
		Rice season, TL, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	**	**
Among F_1, F_2, F_3	**	**	**	**
F_0 v among F_1, F_2, F_3	ns	ns	ns	ns
W x N	ns	ns	ns	ns

Note: ns = not significant; * = significant at 5% level; ** = significant at 1% level.

Higher dry matter (about 2–7%) was observed in continuous flooding than in AWD (figure 6) in Jinhua. In TL, the differences in the total dry matter between W_1 and W_2 in 1999 was 1–22% with consistently higher values in continuously flooded than in AWD treatments, while in 2000, the difference between W_1 and W_2 was small (0.3–5%) and the trend was not consistent among fertilizer treatments (figure 7). In general, the differences due to water treatment in both sites were not statistically significant at 5% level except for the significantly higher total dry matter in F_1 of the continuous flooding treatment in TL compared to AWD in 1999.

Nitrogen Uptake

Nitrogen uptake ranged from 43 to 115 kg N ha^{-1} in Jinhua (figures 8a–d) and 62 to 195 kg ha^{-1} in TL (figures 9a and b). The N uptake tends to increase with the frequency of split applications of N fertilizer. Among the seasons in Jinhua, the average N uptake was highest in 1999, and the lowest was observed in the early rice season in 2000. The low N uptake in the early rice in 2000 was a combination of the lower N concentration in the grain and the low straw N concentration during the early rice seasons (data not shown). In TL, a higher uptake was observed in 2000 than in 1999 in agreement with the higher biomass in 2000.

Figure 8. Effect of water and timing of fertilizer application on total N-uptake. Jinhua, Zhejiang, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 paercent level.

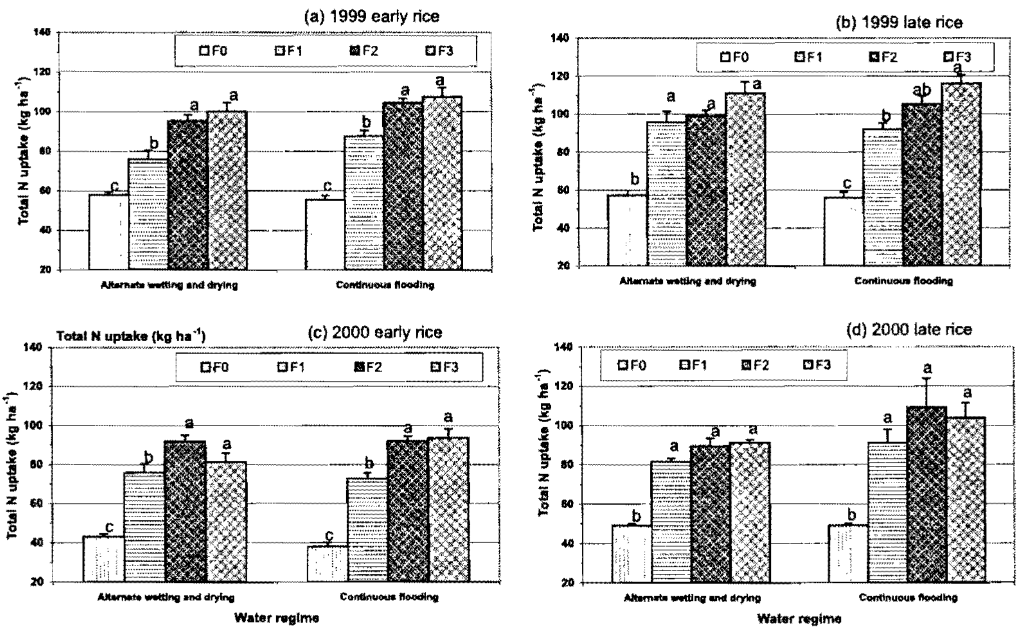
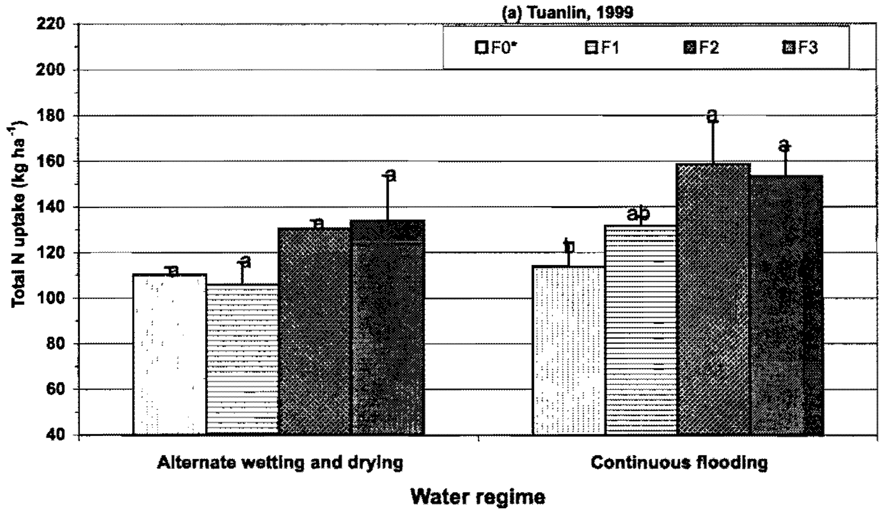
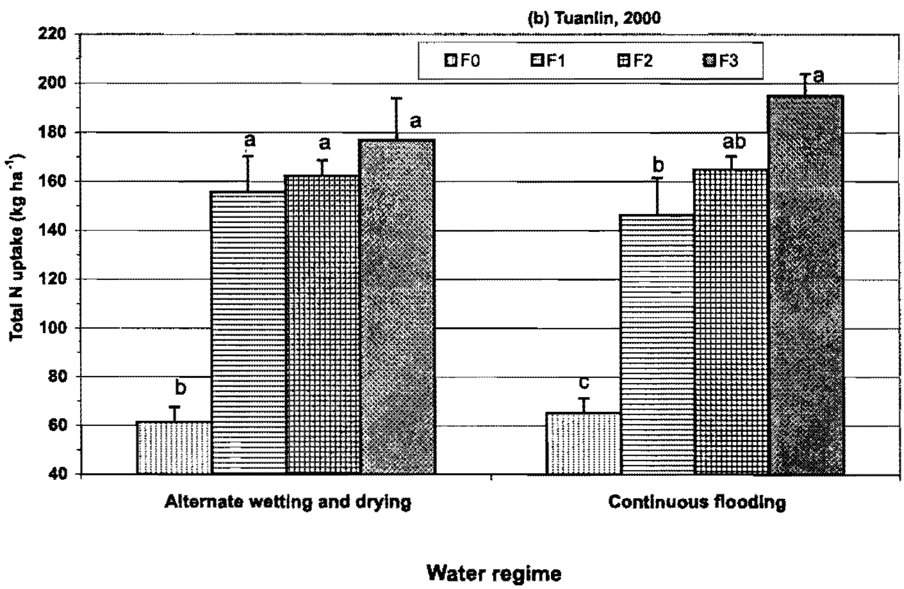


Figure 9. Effect of water and timing of fertilizer application on total N uptake (a) Jinhua, Zhejiang and (b) Tuanlin, Hubei, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.





As in the agronomic parameters, there was no observed W x N interaction on N uptake in crops in 1999 and late rice in Jinhua in 2000 and in both years in TL (table 3). In Jinhua, there was however a significant water-nitrogen interaction with N uptake in early rice in 2000. The fertilizer effect was consistently significant in both years when the basal and control treatments were compared with the mean of fertilizer split N treatments. Among fertilizer splits, the N uptake in farmers' practice of two splits was consistently lower than the N uptake of F_2, and F_3 in Jinhua but the difference was only significant in the early rice crop. Higher uptakes in F_2 and F_3 in both sites were mainly due to a higher N concentration in both grain and straw (data not shown).

At both sites, the difference in N uptake between W_1 and W_2 ranged from 0.2 to 20% depending on the number of fertilizer splits. In most cases, N uptake in the continuously flooded treatment was higher than in the AWD treatment. However, all differences were not significant at 5% level.

Nitrogen Use Efficiency

There was no observed W x N interaction in all N-use efficiency parameters in all seasons in Jinhua and TL (table 4). As in the agronomic parameters, the fertilizer effect was consistently significant when the control was compared with the mean of fertilizer split N treatments. In TL, however, ANUE and AR were not computed in 1999 since the experiment did not include 0-N treatment. The fertilizer effect was not observed in 1999, but it was significant in 2000.

Table 4. Variability of different N-use efficiency parameters as affected by water and timing of fertilizer application, Jinhua and TL, 1999–2000.

Factor	NHI[α]	PNUE[β]	ANUE[χ]	AR[ϕ]
		Early rice, Jinhua, 1999		
Water regime	*	ns	ns	**
Fertilizer	**	**	ns	**
Among F_1, F_2, F_3	ns	**	-	-
F_0 v among F_1, F_2, F_3	**	**	-	-
W x N	ns	ns	ns	ns
		Late rice, Jinhua, 1999		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	ns	*
Among F_1, F_2, F_3	ns	*	-	-
F_0 v among F_1, F_2, F_3	**	**	-	-
W x N	ns	ns	ns	ns
		Early rice, Jinhua, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	ns	**	ns	**
Among F_1, F_2, F_3	ns	*	-	-
F_0 v among F_1, F_2, F_3	ns	**	-	-
W x N	ns	ns	ns	ns
		Late rice, Jinhua, 2000		
Water regime	ns	ns	*	ns
Fertilizer	ns	**	*	ns
Among F_1, F_2, F_3	ns	ns	-	-
F_0 v among F_1, F_2, F_3	*	**	-	-
W x N	ns	ns	ns	ns
		Rice season, TL, 1999		
Water regime	ns	ns		
Fertilizer	ns	ns		
Among F_1, F_2, F_3	ns	ns		
F_0 v among F_1, F_2, F_3	ns	ns		
W x N	ns	ns		
		Rice season, TL, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	ns	**	ns	*
Among F_1, F_2, F_3	ns	*	-	-
F_0 v among F_1, F_2, F_3	ns	**	-	-
W x N	ns	ns	ns	ns

Note: ns = not significant; * = significant at 5% level; ** = significant at 1% level; αNitrogen Harvest Index (NHI) = (grain N uptake / total plant N uptake); βPhysiological N use efficiency (PNUE, kg grain/ kg N uptake) = {(grain yield *0.86) / total plant N uptake};χAgronomic N use efficiency (ANUE, kg grain/ kg N applied) = {(grain yield$_{fertilized}$ – grain yield$_{control}$) * 0.86} / fertilizer N applied; ϕApparent recovery of applied N (AR, %) = (total N uptake$_{fertilizer}$ – total N uptake$_{control}$) / fertilizer N applied * 100

NHI in fertilizer treatments did not vary greatly in all seasons, ranging from 0.56 to 0.76 (table 5 and 6). The relatively high NHI values were probably due to high grain yields and high grain N concentrations (data not shown). The highest NHI was observed in the control treatment. NHI values tended to decline with increasing number of fertilizer split applications, though the level of significance was not consistent among seasons. The relatively high NHI values were probably due to high grain N concentration (data not shown).

Table 5. Nitrogen efficiency parameters as affected by water and timing of fertilizer application, Jinhua, 1999–2000.

Treatment	NHI$^{\alpha}$	PNUE$^{\beta}$	ANUE$^{\chi}$	AR$^{\phi}$	NHI$^{\alpha}$	PNUE$^{\beta}$	ANUE$^{\chi}$	AR$^{\phi}$
AWD irrigation		Early rice, 1999				Late rice, 1999		
F_0	0.76 a	61 a	-	-	0.68 a	66 a	-	-
F_1	0.69 ab	61 a	7 a	12 b	0.62 b	50 b	7 a	26 a
F_2	0.66 b	49 b	7 a	25 a	0.66 ab	47 b	6 a	28 a
F_3	0.65 b	47 b	7 a	28 a	0.65 ab	44 b	7 a	36 a
Continuous flooding								
F_0	0.72 a	66 a	-	-	0.73 a	68 a	-	-
F_1	0.61 b	52 b	6 a	21 b	0.66 b	52 b	6 a	24 b
F_2	0.64 ab	45 b	6 a	33 a	0.67 b	47 bc	7 a	33 ab
F_3	0.64 b	44 b	8 a	35 a	0.64 b	42 c	7 a	40 a
AWD irrigation		Early rice, 2000				Late rice, 2000		
F_0	0.65 a	68 a	-	-	0.69 a	63 a	-	-
F_1	0.63 a	63 ab	13 a	22 b	0.60 a	45 b	4 a	22 a
F_2	0.63 a	55 b	14 a	33 a	0.62 a	43 b	6 a	27 a
F_3	0.61 a	58 ab	12 a	25 b	0.65 a	43 b	6 a	28 a
Continuous flooding								
F_0	0.68 a	72 a	-	-	0.70 a	69 a	-	-
F_1	0.65 ab	63 ab	13 a	23 b	0.62 a	40 b	2 b	28 a
F_2	0.67 ab	54 bc	15 a	36 a	0.66 a	39 b	5 a	40 a
F_3	0.58 b	50 c	13 a	37 a	0.62 a	41 b	6 a	37 a

In a column for each season and water regime, means followed by a common letter are not significantly different at 5% level by DMRT; αNitrogen Harvest Index (NHI) = (grain N uptake / total plant N uptake); βPhysiological N use efficiency (PNUE, kg grain/kg N uptake) = {(grain yield * 0.86) / total plant N uptake}; χAgronomic N use efficiency (ANUE, kg grain/kg N applied) = {(grain yield$_{fertilized}$ – grain yield$_{control}$) * 0.86} / fertilizer N applied; ϕApparent recovery of applied N (AR, %) = {(total N uptake$_{fertilized}$ – total N uptake$_{control}$) / fertilizer N applied} * 100.

Table 6. Nitrogen efficiency parameters as affected by water and timing of fertilizer application, Tuanlin, 1999–2000.

Treatment	NHI[α]	PNUE[β]	ANUE[χ]	AR[φ]
AWD irrigation	Rice season, 1999			
F_0	0.71 a	61 a		
F_1	0.69 a	61 a		
F_2	0.70 a	49 b		
F_3	0.64 a	47 b		
Continuous flooding				
F_0	0.69 a	66 a		
F_1	0.72 a	52 b		
F_2	0.63 a	45 b		
F_3	0.67 a	44 b		
AWD irrigation	Rice season, 2000			
F_0	0.67 a	62 a	-	-
F_1	0.60 a	50 b	21 a	52 a
F_2	0.60 a	45 b	19 a	56 a
F_3	0.58 a	43 b	20 a	64 a
Continuous flooding				
F_0	0.63 a	59 a	-	-
F_1	0.57 a	50 b	18 a	45 b
F_2	0.56 a	43 bc	18 a	55 ab
F_3	0.67 a	39 c	20 a	72 a

In a column for each season and water regime, means followed by a common letter are not significantly different at 5% level by DMRT; aNitrogen Harvest Index (NHI) = (grain N uptake / total plant N uptake); bPhysiological N use efficiency (PNUE, kg grain/ kg N uptake) = {(grain yield * 0.86) / total plant N uptake}; cAgronomic N use efficiency (ANUE, kg grain/kg N applied) = {(grain yield$_{fertilized}$ – grain yield$_{control}$) * 0.8 6} / fertilizer N applied; fApparent recovery of applied N (AR, %) = {(total N uptake$_{fertilized}$ – total N uptake$_{control}$) / fertilizer N applied} * 100.

PNUE values ranged from 39 to 72 kg grain/kg N uptake with decreasing values as the number of splits increased (tables 5 and 6). PNUE values tend to decrease with increasing N splits. This was reflected in the higher N concentrations in both the grain and straw (data not shown) in F_2 and F_3 compared with F_0 and F_1.

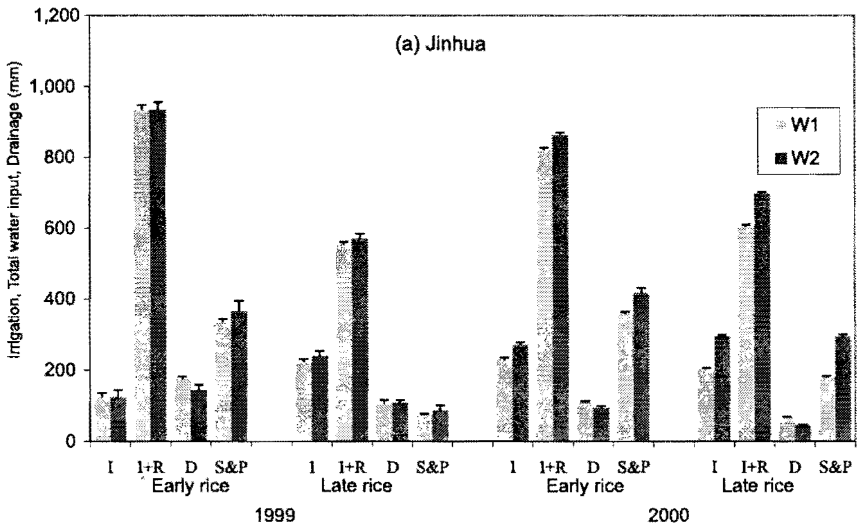
ANUE values ranged from 2 to 15 kg grain/kg N applied (table 5) in Jinhua and from 18 to 21 kg grain/kg N applied in TL (data available only for year 2000) (table 6). ANUE values in F2, F3 and F1 were comparable.

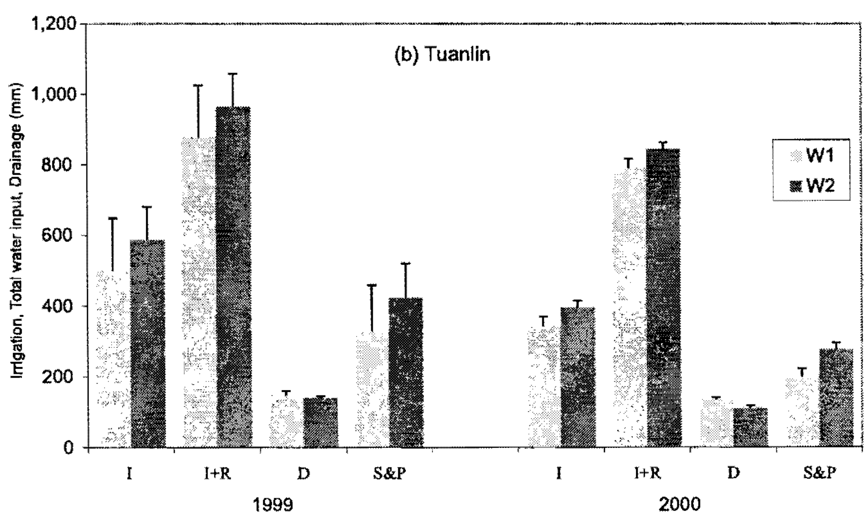
Values of AR ranged from 12 to 40% in Jinhua (table 5) and 45 to 72% in TL (only in year 2000) (table 6). The increase in AR in F_2 and F_3 conforms to the increase in N uptake with the increasing number of splits. ANUE and AR values in TL were higher than in Jinhua. This was because the difference between the zero N and other N treatments was higher in TL (about 4 t ha^{-1}) than in Jinhua (about 3 t ha^{-1}).

Drainage, Seepage and Percolation

The amount of drainage water was higher in W_1 than W_2, significant at 5% level in both sites in 2000 and in the early rice of 1999 (figure 10). The higher drainage water observed in W_1 was because water was deliberately drained to realize the periodic drying, especially in the long drying period (mid-season drainage) at the tillering stage.

Figure 10. Water balance components in alternate wetting and drying (w_1) and continuous flooding (w_2) in 1999 and 2000 in (a) Jinhua, Zhejiang Province and (b) Tuanlin, Hubei Province, P. R. China.





In TL, the daily seepage and percolation rates in replication 1 of treatment W_1 was exceedingly higher (>20 mm day^{-1}) than in other replications (<6 mm day^{-1}). This was because there was a drainage pipe network previously installed in replication 1 of treatment W_1. This replication was removed for our subsequent analysis of water balance and water productivity. The mean seepage and percolation rate for other replications was 4–6 mm day^{-1} in 1999 and 3 mm day^{-1} in 2000. The lower seepage and percolation rates in 2000 could be attributed to the construction of cement linings along the main plots in 2000.

The mean seepage and percolation rate in Jinhua was 3.8 mm day^{-1}, varying from 1 to 6 mm day^{-1}. At both sites, there was no significant difference in seepage and percolation rates between the two water treatments. Over the crop season, the total amount of seepage and percolation was consistently higher in W_2 than in W_1 at both sites, but the differences were significant only in 2000 (figure 10). Since there were no significant differences in S&P rates between W_1 and W_2, the higher amount of total seepage and percolation in W_2 can be attributed to the greater number of days with standing water in W_2.

Water Input

In Jinhua, the total water input (rainfall + irrigation) ranged from 554 to 934 mm per crop. The total water input in early rice crops was invariably higher than in the late rice crops (figure 10). This was due to the higher rainfall in the early rice crop. Irrigation water in the late season crop of 1999 (about 230 mm) was much higher than the early season crop of 1999 (about 120 mm). This conforms to the higher rainfall in the early rice season in 2000. Despite the high rainfall in the early rice crop of 2000, the amount of irrigation water was comparable to that in the late rice crop. This was due to the high evaporative demand in the season (table 2). In TL, the total water input ranged from 732 to 1,144 mm. The total water input in 1999 (930 mm) was higher than in 2000 (820 mm) (figure 10). This was due to the lower rainfall in 1999 (table 2).

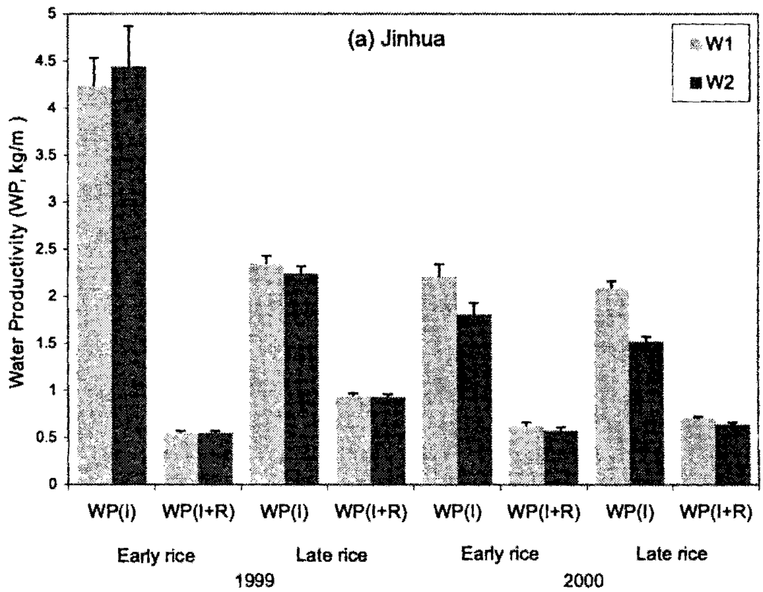
In most cases, irrigation under continuous flooding treatment was higher than under AWD but the differences were statistically significant only in the year 2000, when larger irrigation amounts were required. The largest difference in irrigation water between the two water treatments occurred in Jinhua in the late rice season of 2000.

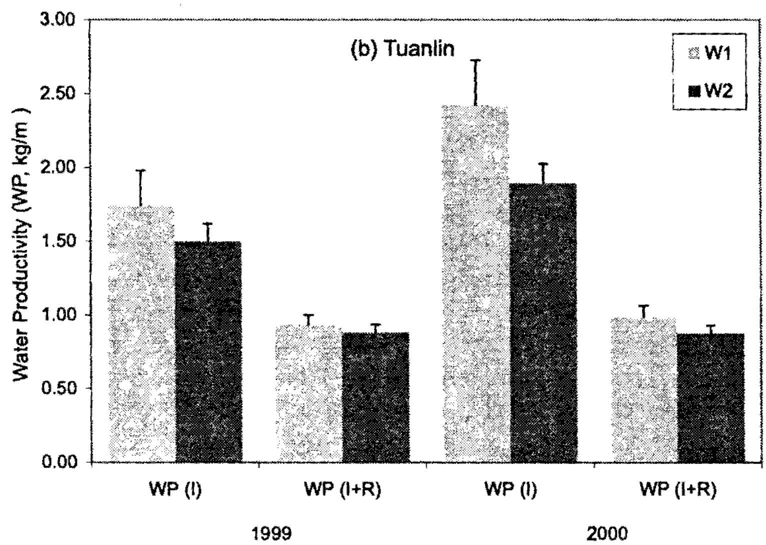
Water Productivity

Water productivity in terms of total water input (irrigation + rainfall, WP_{IR}) ranged from 0.55 to 0.94 kg m^3 in Jinhua, and from 0.87 to 0.98 kg m^3 in TL (figure 11). In both sites, WP_{IR} was generally higher in W_1 than in W_2 but the difference was statistically significant in Jinhua, only in the late rice season of 2000 (figure 11).

Water productivity in terms of irrigation (WP_I) ranged from 2.1 to 4.2 kg m^3 in Jinhua, and from 1.50 to 2.42 kg m^3 in TL. WP_I in Jinhua was higher in the early rice crop than in the late rice crop because of lower irrigation water input in the early rice. As in TL, WP_I was higher in 2000 than in 1999, due to the lower irrigation water input in 2000. WP_I was higher under AWD than under continuous flooding in three out of four seasons in Jinhua (except for the early rice crop of 1999), and in both years in TL. In these cases, the increase in WP_I was mainly due to the lower irrigation water input in W_1 (figure 10). For the early rice crop of 1999, WP_I under continuous flooding was slightly higher than that under AWD because the amount of irrigation was similar in both treatments while the yield under continuous treatment was slightly higher than under AWD.

Figure 11. Water productivities with respect to irrigation (WPI) and to the total water input ($WP_{(I+R)}$) in alternate wetting and drying (W_1) and continuous flooding (w_2) in 1999 and 2000 in (a) Jinhua, Zhejiang Province, and (b) Tuanlin, Hubei Province, P. R. China.





Conclusions

Increasing the number of splits increased the total N uptake, but not the grain yield and biomass compared to farmers' practices of two splits. In most cases, continuous flooding gave 1–25% higher yields than AWD, though there are cases where AWD gave higher yields. However, the yield differences were not statistically significant at 5% level. Our study showed that periodic drying of the soil was not a prerequisite for high yield. There was no significant water-nutrient interaction on grain yield, biomass and N uptake. Thus, AWD does not require N-fertilizer management differently from continuous flooding

In our study, AWD reduced irrigation only by a small amount if measured in absolute terms (maximum 90 mm in Jinhua, maximum 80 mm in TL) compared to continuous flooding. But this saving accounted up to 30% of the irrigation water. This is because the study sites had relatively high rainfall, low percolation and seepage and, therefore, a low total of irrigation water. Nevertheless, AWD could raise the water productivity with respect to irrigation water by about 5–35% compared to continuous flooding in Jinhua, and by 16–28% in TL. The amount of water saved and the increase in water productivity will probably become more important in more-pronounced dry conditions or in more-permeable soils. Farmers can also reduce the amount of irrigation further by not having to drain the field to achieve periodic drying. AWD can thus be an important technology for farmers to cope with water scarcity and may help increase water productivity at the regional scale if on-farm water saved can be used more productively downstream.

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