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ORIGINAL ARTICLE

Drought response of dry-seeded rice to water stress timing and N-fertilizer rates and sources

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Abstract

Dry seeding has been identified as an option for increasing cropping intensity and productivity in rainfed ricelands. Managing drought and nutrients are important for increasing yield, but the interactive effects of drought and nutrients on dry-seeded rice (*Oryza sativa* L.) growth have not been systematically investigated. Two experiments were carried out in 1994 and 1995 to analyze the effects of N fertilizer rate and the use of controlled-release fertilizers (CRFs) on the growth and yield of dry-seeded rice grown on a silty clay loam (Typic Tropaquept) subjected to water stress at different crop stages. In both years, in the main plots, rice was subjected to water stress at four different stages of development. The subplots were designed to compare the effect of the application of prilled urea and CRFs Osmocote (1994) and Polyon 12 (1995). Four N rates (0, 60, 120 and 180 kg ha^{-1}) were imposed on rice in the sub-subplots (1994 only). The N fertilizer source did not affect any of the measured parameters. Irrespective of the N the fertilizer rates, grain yield and total dry matter accumulation of rice plants stressed at the flowering stage (WS$_{FL}$, 1994) and panicle initiation stage (WS$_{PI}$, 1995) were significantly lower than those of well-watered plants and plants stressed at the vegetative stage. Water stress during the grain-filling stage reduced the grain yield in 1995 when the stress was severe. Application of N fertilizer increased the yield compared with zero N in all water treatments, except for the WS$_{FL}$ plants whose yield did not change. The WS$_{FL}$ treatment also significantly reduced agronomic N-use efficiency.

Key words: controlled-release fertilizer, direct seeding, nutrient/water interaction, rainfed rice, water stress, yield loss.

INTRODUCTION

The rainfed lowland rice ecosystem accounts for 25% of the total world rice area, but contributes to a mere 18% of world rice production (International Rice Research Institute 1993). The relatively low productivity in this ecosystem may be partly attributed to drought, low nutrient levels or both. Dry seeding (broadcasting of seeds on dry or moist non-puddled soils) is an option for increasing cropping intensity and productivity in rainfed areas. This method enables the use of early-season rainfall more effectively to advance land preparation and crop establishment and to reduce exposure to late-season drought because sufficient residual soil moisture may remain for the cultivation of an upland crop after rice (Tuong *et al.* 1995).

The effects of water deficit at different intensities and times on the phenological development, crop growth and grain yield of transplanted (TP) rice have been well documented (Boonjung and Fukai 1996; Castillo *et al.* 1992; Lilley and Fukai 1994; Wopereis *et al.* 1996; Yambao and Ingram 1988). However, quantitative data on the drought response of dry-seeded (DS) rice are limited. It is possible that stress effects are modified by crop establishment methods and soil conditions. Boling *et al.* (1998) showed that, compared with TP rice, DS rice displayed a higher value of total root length, a more uniform root distribution and, hence, a more uniform water extraction pattern in relation to soil depth.

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Tuong *et al.* (2002) obtained a higher yield of DS rice than of TP rice when both were subjected to water stress at the panicle initiation stage (PI). The response of DS rice to stress timing, which may be modified further by inter- and intraplant competition because of high plant density and excessive vegetative growth (Tuong *et al.* 2000), has not been investigated systematically.

Increasing N availability to the plant has been found to increase yield in drought-prone rainfed rice (Boling *et al.* 2004; Khonthasuvon *et al.* 1998; Wade *et al.* 1999). The most common method to achieve this objective is to increase the amount of urea fertilizer applied. A unique feature of rainfed systems is the alternation between aerobic and anaerobic soil conditions, which promotes nitrification and results in the subsequent loss of N and lower N-use efficiency because of leaching and denitrification. This may be exacerbated in DS rice because of the higher percolation rate associated with the lack of puddling (Tuong *et al.* 2002). Increasing the amount of N fertilizer may also increase the risk of higher N loss. One possible approach to reduce this risk is the use of controlled-release fertilizers (CRFs), whose nutrient release is almost independent of the soil moisture regime (Gandeza and Shoji 1992). Singh *et al.* (1995) reported that grain yield under irrigated conditions from a single application of CRFs was equivalent to or higher than that achieved with 3–4 split-N applications. Tuong *et al.* (2002), however, observed that when the plants were stressed at the PI stage, CRF Polyon 12 gave a lower yield than prilled urea (PU). This was probably because of a mismatch between drought-induced prolongation of crop duration and the release period of Polyon 12. It is possible that CRFs may have a relative advantage over PU in lighter soils, which are more prone to nitrate leaching than clay soils, and when the plants are stressed at different stages of development such as at the flowering and grain-filling stages, when stress does not prolong crop duration (Wopereis *et al.* 1996).

The objective of the present study was to investigate the effects of drought stress at different crop stages on the development, growth and yield of DS rice and its N-use efficiency, as well as to test the hypothesis that increasing nutrient availability to plants through higher N application rates and the use of CRFs can mitigate the effect of drought on DS rice growth.

MATERIALS AND METHODS

Experimental site and conditions

Two field experiments were conducted in farmers' fields from March to June 1994 and from February to May 1995 at Tarlac, Philippines (15°62′ N, 120°73′ E). The site was characterized by two distinct seasons: a dry season from December to April and a rainy season from May to November. Based on the soil taxonomy (Soil Survey Staff 1992), the experimental soil was a silty clay loam Typic Tropaquept, with 38% clay, 42% silt and 20% sand, and 0.85% organic carbon in the topsoil (0–20 cm).

Total rainfall during the 1994 experiment was 509 mm, which fell mostly during May–June (day of the year = 122–182, Fig. 1a), while 379 mm fell in 1995, mostly in May (Fig. 1b). The mean temperature was higher in 1994 than in 1995 during the early part of the growth season, but the reverse was true during the latter period of crop growth. Average maximum temperatures were 33.9°C and 33.4°C in 1994 and 1995, respectively. Total solar radiation was higher in 1995 (2745 MJ m^{-2}) than in 1994 (2309 MJ m^{-2}).

Experimental design and cultural practices

The experiments consisted of four replications in a split-split-plot design in 1994 and a split-plot design in 1995. Rice plants in the main plots in 1994 were either not subjected to water stress conditions (WW: well-watered plants or absence of stress throughout the duration of plant growth) or subjected to water stress as follows: WS_{TL}: stress at the maximum tillering stage (MT), WS_{FL}: stress at the flowering stage (FL) and WS_{GF}: stress at the grain-filling stage (GF). Similar water stress timings were used in 1995, except that WS_{FL} was replaced with WS_{PI}: stress at the panicle initiation stage (PI). The main plots in both experiments were hydraulically isolated using plastic sheets installed to a depth of 0.60 m to prevent lateral movement of water.

The subplots were designed to compare the effect of two fertilizer sources: conventional prilled urea (PU) in both 1994 and 1995, and CRF Osmocote (1994) or Polyon 12 (1995). In 1994, the subplots were further divided into four N rates (0, 60, 120 and 180 kg N ha^{-1} or N_0, N_{60}, N_{120} and N_{180}, respectively), while 100 kg N ha^{-1} was used in 1995 in all the subplots. The sub-subplots in 1994 measured 24 m^2 and the subplots in 1995 measured 40 m^2.

Before land preparation, weeds were cut and removed and the field was dry-plowed and roto-tilled to a depth of approximately 15 cm using a hydro-tiller. During the final harrowing, 25 (1994) and 40 (1995) kg P ha^{-1} (single superphosphate), and 25 (1994) and 40 (1995) kg K ha^{-1} (KCl) were applied as basal dressing. The P and K amounts were increased in 1995 to secure adequate P and K availability. Rice cvs IR72 (1994) and PSBRc 14 (1995) were dry-seeded at a rate of 100 kg ha^{-1} at a 2-cm depth in rows spaced at 20 cm.

All plots were flush irrigated daily until the crop was fully established. Thereafter, all plots were flooded to a

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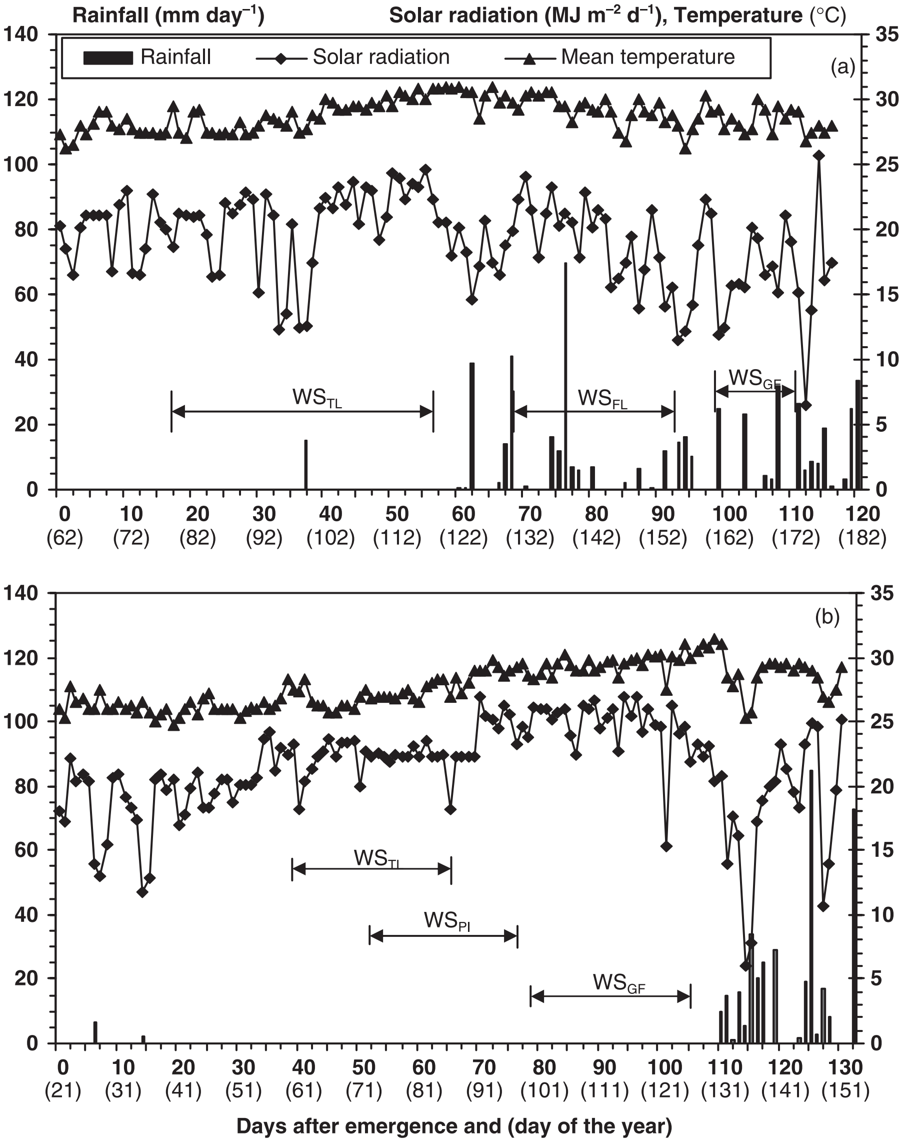

Figure 1 Daily mean air temperature, rainfall and solar radiation during the (a) 1994 and (b) 1995 experiments. WS_{TL}, stress at the tillering stage; WS_{PI}, stress at the panicle initiation stage; WS_{FL}, stress at the flowering stage, WS_{GF}, stress at the grain-filling stage.

depth of approximately 5 cm. In the drought treatments, water was drained at the start of each stress period and irrigation was withheld until the leaf-rolling score reached a value of 5 (O'Toole *et al.* 1979). When rainfall during the stress period (such as in 1994; Fig. 1a) prevented the attainment of the desired stress level, the stress was terminated before the crop reached the subsequent phenological phase. Tables 1 and 2 summarize the timing and duration of the stress periods in 1994 and 1995.

Conventional prilled urea was applied in four equal splits: 15 days after seeding (DAS) and at the MT, PI and FL stages in both years. In the drought stress treatments, application of PU topdressing was delayed until the stress had been removed to avoid drought-induced N losses. The CRFs were applied by row seeding and incorporated at a depth of 1–2 cm by covering with soil in one single dose at the time of seeding in both experiments.

Soil, water and climatic data determinations

Soil samples for the 0–5, 5–20 and 20–40-cm depths were taken on the first day of the stress in 1994 to determine the water retention characteristics using the pressure membrane method. Periodic soil sampling at the 0–5, 5–20 and 20–40-cm depths was undertaken during the stress periods for soil moisture determination. At each sampling, five cores (5 cm diameter) were

Table 1 Timing of stress imposition, topdressing of prilled urea (PU), plant sampling and phenological development of IR72 (1994 dry season)

	Date (and days after emergence)								
Events	21 Mar. (18)	27 Apr. (55)	29 Apr. (57)	11 May (69)	26 May (84)	04 Jun. (93)	10 Jun. (99)	20 Jun. (109)	30 Jun. (119)
Well-watered plants (WW)									
Crop stage		PI			FL			Har	
Stress at tillering stage (WS_{TL})									
Stress	Start		End						
Crop stage				PI		FL			Har
Stress at flowering stage (WS_{FL})									
Stress				Start			End		
Crop stage		PI			FL			Har	
Stress at grain-filling stage (WS_{GF})									
Stress						Start		End	
Crop stage		PI			FL			Har	

FL, flowering; Har, harvest; PI, panicle initiation.

Table 2 Timing of stress imposition, top dressing of prilled urea (PU), plant sampling and phenological development of PSBRc14 (1995 dry season)

	Date (and days after emergence)												
Events	25 Feb. (40)	17 Mar. (55)	19 Mar. (57)	25 Mar. (63)	04 Apr. (73)	06 Apr. (75)	08 Apr. (77)	12 Apr. (81)	26 Apr. (95)	03 May (102)	11 May (110)	23 May (122)	28 May (127)
Well-watered plants (WW)													
Crop stage			PI		FL						Har		
Stress at tillering stage (WS_{TL})													
Stress	Start			End									
Crop stage							PI		FL				Har
Stress at panicle initiation stage (WS_{PI})													
Stress		Start				End							
Crop stage			PI						FL			Har	
Stress at grain-filling stage (WS_{GF})													
Stress								Start		End			
Crop stage			PI		FL					Har			

FL, flowering; Har, harvest; PI, panicle initiation.

collected randomly from each sub-subplot (1994) or subplot (1995) using a soil auger.

Rainfall, maximum and minimum temperatures and solar radiation were recorded daily from a meteorological station located approximately 20 m from the experimental site.

Plant sampling and yield parameters

Periodic plant samplings (2 rows × 0.5 m) were carried out in each plot at critical growth stages and during the stress periods for the determination of biomass and its partitioning and for yield component analysis. At the final harvest, rice plants from designated 9 rows × 3 m were cut at the ground level and threshed manually for grain yield determination. Samples were dried at 70°C until they reached a constant weight. The reported grain yield was adjusted to 14% moisture. In 1994, subsamples of straw and grain were ground using a Beater Cross grinder and analyzed for N content using the micro-Kjeldahl method (Bremner and Mulvaney 1982). Total N content in the straw and grain was calculated from the amount of grain and straw dry matter and their respective N contents. We calculated

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the apparent N recovery (REN, in kg N kg N applied^{-1}) as the N uptake in fertilized plots minus the N uptake in unfertilized plots divided by the N application rate. Agronomic N-use efficiency (AEN, kg grain kg N applied^{-1}) was calculated from the difference in grain yield between fertilized and unfertilized plots divided by the N application rate; while physiological N-use efficiency (PEN, kg grain kg^{-1} N uptake) was calculated as the grain yield divided by the total N uptake. When the grain yields of the fertilized plots were less than those of the unfertilized plots, AEN was given a value of zero (instead of being negative).

Data analysis

Soil, plant and nitrogen data were analyzed using standard split-split-plot (1994) and split-plot (1995) ANOVAs using IRRISTAT 4.0 for Windows (International Rice Research Institute 2004). In the absence of three-way and two-way interactions between water, N source and N rate treatments, the reported data of a treatment were pooled across the other experimental factors.

RESULTS AND DISCUSSION

Soil water content

No differences in the soil water content across the N treatments were observed (data not shown). Volumetric water contents at different depths were pooled across N rates and sources (see Fig. 2 for 1994 and Fig. 3 for 1995).

In 1994, 15.3 mm of rainfall during the WS_{TL} treatment (20 days after stress imposition; Fig. 1a) delayed the attainment of the desired leaf rolling score of 5 that was set for the termination of the stress treatment until 40 days after the onset of the stress. Soil water content at the 0–5-cm (Fig. 2a) and 5–20-cm depths (Fig. 2b) during the WS_{TL} treatment decreased to below the permanent wilting point (PWP) for a large part of the stress period. Soil water content at the 20–40-cm depth also reached the PWP toward the end of the stress period (Fig. 2c). During the WS_{FL} treatment, the soil water content at the 0–5-cm depth decreased to below the PWP during the dry spell that occurred approximately 15 days after stress initiation (Fig. 2a), while the soil water content for most of the time and for the other soil layers did not reach the PWP. High and frequent rainfall during the WS_{GF} treatment (Fig. 1a) kept the soil water content of the root zone around the field capacity (data not shown).

In 1995, there was no rainfall throughout the duration of all the stress periods (Fig. 1b). A leaf rolling score of 5 was reached after 28 days of the WS_{TL} treatment and 20 days of the WS_{PI} treatment. Soil water content at all the soil depths decreased progressively with time during each stress period (Fig. 3). Soil water content of the 0–5 cm soil layers reached the PWP 4–6 days after stress initiation, while the water content at the 5–20-cm and 20–40-cm depths reached the PWP only after approximately 8 and 16 days, respectively, toward the end of the stress period.

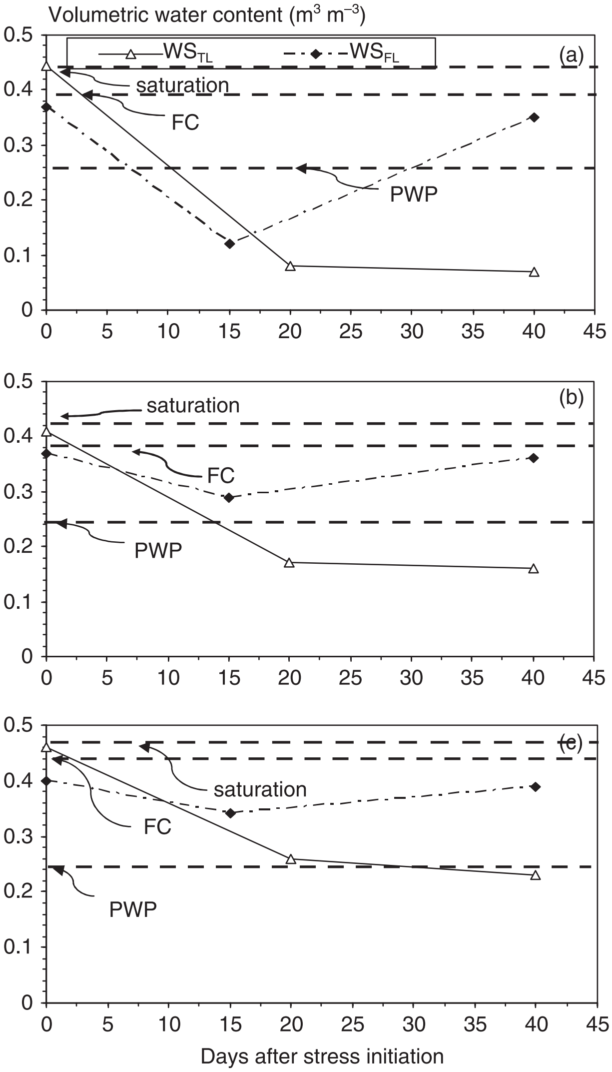

Figure 2 Soil water content at (a) 0–5-cm, (b) 5–20-cm and (c) 20–40-cm depths during water stress at the tillering (WS_{TL}) and flowering (WS_{FL}) stages (1994). Data were averaged over two N sources and four N rates. FC, field capacity; PWP, permanent wilting point.

In summary, water stress in 1995 was much more severe than in 1994. In 1994, the stress level at the TL stage was more severe than that at the FL stage, and the latter was more severe than that at the GF stage. Periodic rainfall during stress imposition at the FL and GF stages prevented the attainment of the leaf rolling score of 5 at the end of the stress periods.

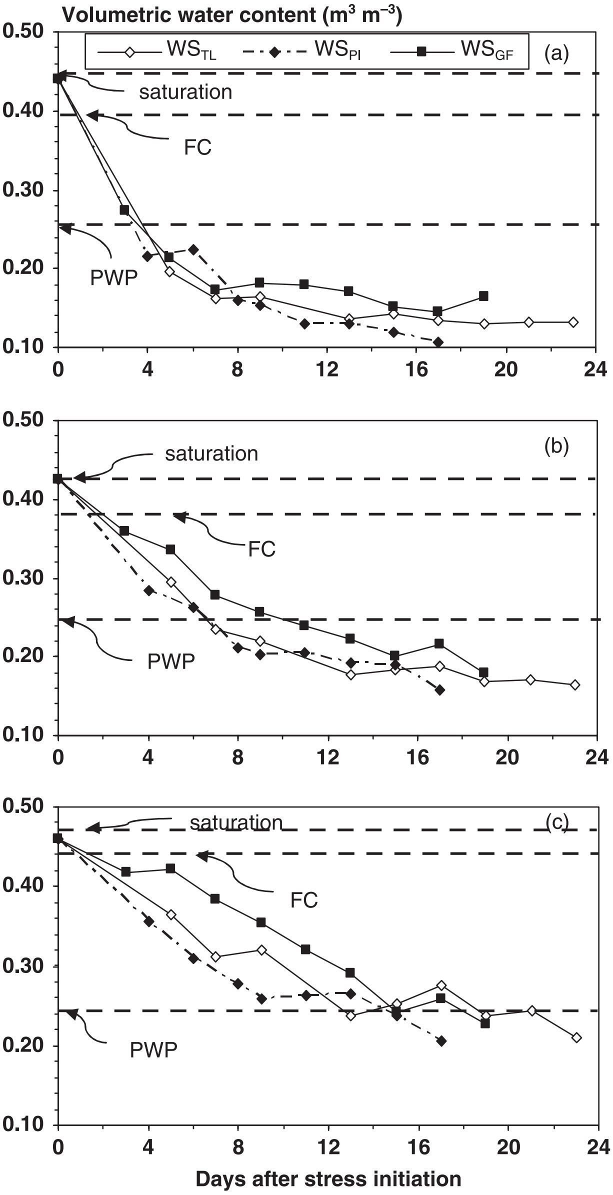

Figure 3 Soil water content at (a) 0–5-cm, (b) 5–20-cm and (c) 20–40-cm depths during water stress at the tillering (WS_{TL}), panicle initiation (WS_{PI}) and grain-filling (WS_{GF}) stages of IR72 (1995). Data were averaged over two N sources. FC, field capacity; PWP, permanent wilting point.

Effects on phenology

In both experiments, phenological development was unaffected by the source or rate of fertilizer applied (data not shown). However, in both years the WS_{TL} plants displayed a delay in flowering and harvest compared with the well-watered plants. The delay in 1995 was longer that in 1994 (Table 1 vs Table 2) because the stress in 1995 was more severe than in 1994. Similarly, flowering of the WS_{PI} plants in 1995 was delayed by 22 days and physiological maturity (harvest) by 12 days (Table 2). Withholding irrigation during the flowering and grain-filling stages in 1994 did not affect phenological development. In 1995, the plants subjected to the WS_{GF} treatment were harvested 8 days earlier than the well-watered plants. Severe stress at the GF stage in 1995 was associated with increased leaf senescence (Wopereis *et al.* 1996), while stress at the GF stage in 1994 was not severe enough to cause visible effects. The findings in the present study support those previously reported and showed that the effect of water stress on the phenological development of DS rice was similar to that of TP rice (Boling *et al.* 1998; Tuong *et al.* 2002; Wopereis *et al.* 1996).

Variability of yield and N parameters

Table 3 (for 1994) and Table 4 (1995) summarize the effects of water, N rate and N source treatments and their interactions on straw and grain yields, total dry matter accumulation, harvest index (HI), N uptake and N-use efficiency (only for 1994). The effect of the N source was not significant for all the listed parameters in both years. Water (in 1994 and 1995) and N-rate (1994) significantly affected ($P < 0.05$) most of the parameters examined (except for straw yield, and straw N uptake for water; and HI, AEN and REN for N rates).

The water/N-rate interaction was significant for grain yield, total dry matter accumulation as well as for grain, straw and total N uptake. The water/N-source interaction was significant only on grain N-uptake in 1994. The N rate interaction with N source and the three-way interaction did not exert a significant effect on any of the listed parameters in 1994 (Table 3).

Crop growth and grain yield

Effect of N source

Figures 4 and 5 show a comparison of the time-course of total dry matter accumulation of DS rice subjected to different N rates and water treatments in 1994. Tables 5 and 6 summarize the effects of water and N management on final dry matter accumulation, straw and grain yields and HI in 1994 and 1995. The data in the figures and tables are averages for the N sources because there was no significant effect of N source or interactions with N rate.

The non-significant effect of N source on rice yield differed from the results obtained by Tuong *et al.* (2002) in a heavy clay soil where grain yield with CRF Polyon 12 application was significantly lower than that with multi-split PU application when the crop was subjected to water stress at the PI stage. They attributed the decrease of rice yield under CRF Polyon 12 to the

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Table 3 Level of significance of different yield parameters, plant N-uptake and N-use efficiency of IR72 as affected by water stress, N source and rate of fertilizer application (1994 dry season)

Effects	Grain yield ($t\ ha^{-1}$) $P > F^{\dagger}$	Straw yield ($t\ ha^{-1}$) $P > F$	Total dry matter accumulation ($t\ ha^{-1}$) $P > F$	Grain N uptake ($kg\ ha^{-1}$) $P > F$	Straw N uptake ($kg\ ha^{-1}$) $P > F$	Total N uptake ($kg\ ha^{-1}$) $P > F$	HI[‡] $P > F$	PEN[§] $P > F$	AEN[¶] $P > F$	REN[††] $P > F$
Water (W)	0.003	0.971	0.019	0.004	0.206	0.032	0.003	0.004	0.017	0.053
Nitrogen source (NS)	0.514	0.156	0.198	0.922	0.700	0.761	0.677	0.342	0.778	0.884
W and NS interaction	0.133	0.422	0.530	0.038	0.955	0.465	0.167	0.334	0.990	0.824
Nitrogen rate (NR)	0.038	0.002	0.003	0.021	0.001	0.001	0.087	0.002	0.161	0.184
W and NR interaction	0.001	0.430	0.046	<.001	0.017	0.001	0.001	0.050	0.068	0.538
NS and NR interaction	0.248	0.122	0.133	0.190	0.969	0.483	0.313	0.611	0.248	0.756
W, NR and NS interaction	0.741	0.677	0.694	0.388	0.855	0.361	0.693	0.564	0.920	0.842

[†] $P > F$, probability higher than the critical F value. [‡] Harvest index (HI) = grain yield for oven-dry moisture content/total dry matter. [§] Physiological N-use efficiency (PEN, kg grain kg N uptake^{-1}) = grain yield*0.86/total plant N uptake. [¶] Agronomic N-use efficiency (AEN, kg grain kg N applied^{-1}) = grain yield$_{fertilized}$ – grain yield$_{control}$*0.86/N applied. [††] Apparent recovery of applied N (REN, %) = total N uptake$_{fertilized}$ – total N uptake$_{control}$/ fertilizer N applied × 100.

Table 4 Level of significance of different agronomic parameters of PSBRc14 as affected by water stress and fertilizer source (1995 dry season)

Effects	Grain yield ($t\ ha^{-1}$) $P > F^{\dagger}$	Straw yield ($t\ ha^{-1}$) $P > F$	Total dry matter accumulation ($t\ ha^{-1}$) $P > F$	HI[‡] $P > F$
Water (W)	0.012	0.010	0.013	0.011
Nitrogen Source (NS)	0.967	0.846	0.878	0.870
W and NS interaction	0.492	0.674	0.697	0.433

[†] $P > F$, probability higher than critical F value. [‡] Harvest index (HI) = grain yield for oven-dry moisture content/total dry matter.

Table 5 Grain and straw yield, total dry matter accumulation and harvest index of IR72 as affected by water (W) and fertilizer rates (NR) and their interaction (1994 dry season)

	Grain yield ($t\ ha^{-1}$)				Straw yield ($t\ ha^{-1}$)				Total dry matter accumulation ($t\ ha^{-1}$)				HI[§]			
Treatment	WW	WS_{TL}	WS_{FL}	WS_{GF}	WW	WS_{TL}	WS_{FL}	WS_{GF}	WW	WS_{TL}	WS_{FL}	WS_{GF}	WW	WS_{TL}	WS_{FL}	WS_{GF}
(NR)[†]																
0	2.8 b[‡]	3.9 b	1.1 a	3.4 bc	3.6 b	3.9 b	3.4 b	3.2 b	6.4 b	7.8 b	4.4 b	6.7 c	0.41 a	0.47 a	0.24 a	0.48 a
60	4.4 a	5.2 a	1.0 a	3.5 b	5.0 a	5.3 a	4.9 a	4.7 a	9.3 a	10.5 a	5.9 ab	8.2 b	0.44 a	0.46 a	0.16 b	0.40 b
120	4.9 a	4.9 ab	1.0 a	5.1 a	5.7 a	5.4 a	5.6 a	5.7 a	10.6 a	10.3 a	6.6 a	10.8 a	0.43 a	0.44 a	0.12 b	0.45 ab
180	4.6 a	4.5 ab	0.3 a	5.3 a	5.8 a	5.2 a	6.2 a	5.5 a	10.3 a	9.7 a	6.5 a	10.8 a	0.42 a	0.43 a	0.05 c	0.46 ab
[¶] $LSD_{0.05}$	1.4				0.6				2.1				0.12			

[†] Means are the average over two fertilizer sources. [‡] In each column, means followed by the same letter (a,b,c) are not significantly different at the 5% level using Duncan Multiple Range Test (DMRT). [§] Harvest index (HI) = grain yield for oven-dry moisture content/total dry matter. [¶] Least significant difference ($LSD_{0.05}$) was used to compare two W means at each NR.

drought-induced prolongation of crop duration: as the crop matured late after the release period of Polyon 12, N was released before the plant could take it up, presumably resulting in larger losses compared with PU application in small doses at several stages.

According to the manufacturers, the duration of the release period of CRF Polyon 12 is 102 days at a constant temperature of 30°C and the release period of CRF Osmocote is 120 days at 25°C, both under vapor-saturated conditions. The mean soil temperature at the 10-cm depth was estimated at 28°C using the relationship between air and soil temperature under rice cultivation, based on experimental data obtained at International Rice Research Institute (C. Witt, unpubl. data, 1994). Therefore, these release periods are likely to be good approximations of the actual release in our experiments.

In 1994, the duration of the release period of CRF Osmocote under the experimental conditions was

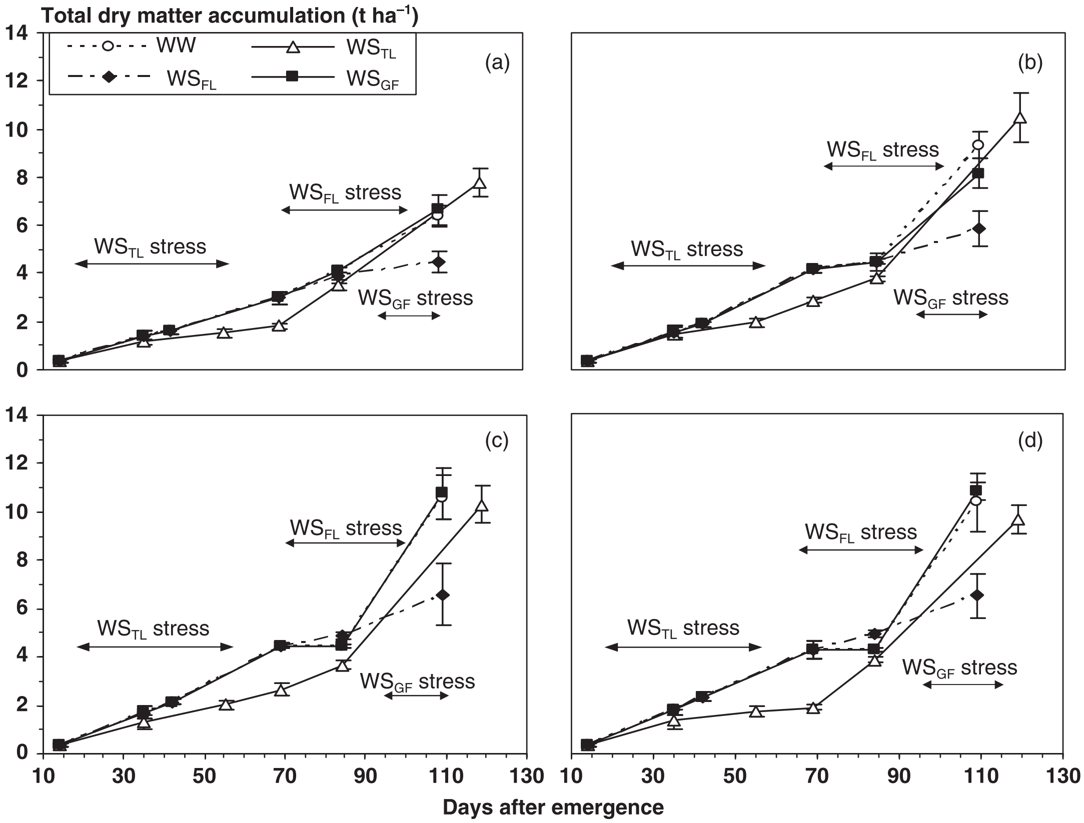

Figure 4 Total dry matter accumulation of IR72 at (a) 0, (b) 60, (c) 120 and (d) 180 kg N ha^{-1} as affected by water stress. Mean ± standard error. Data were averaged over two N sources and four replications. WW, well-watered plants; WS_{TL}, stress at the tillering stage; WS_{FL}, stress at the flowering stage; WS_{GF}, stress at the grain-filling stage.

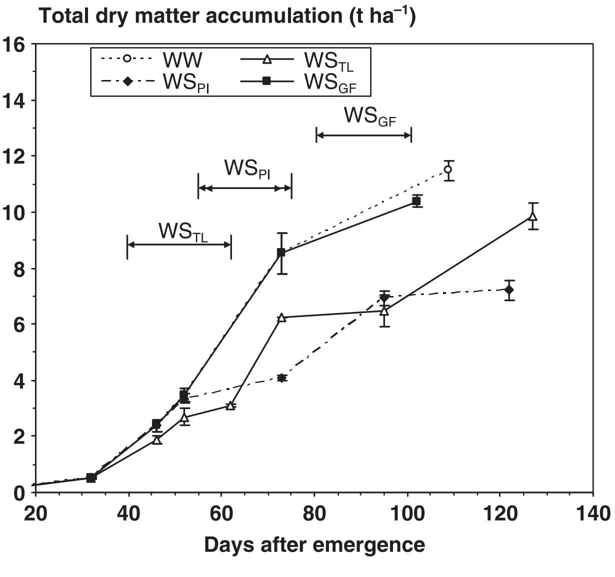

Figure 5 Total dry matter accumulation of PSBRc 14 as affected by water stress. Mean ± standard error. Data were averaged over two N sources and four replications. WW, well-watered plants; WS_{TL}, stress at the tillering stage; WS_{PI}, stress at the panicle initiation stage; WS_{GF}, stress at grain-filling stage.

probably slightly longer than the crop duration in the WW, WS_{FL} and WS_{GF} treatments (approximately 110 days; Table 1) and was comparable with that of WS_{TL} (119 days). As both CRF Osmocote and split-applied PU could supply N throughout the crop season, the effects on crop performance were similar.

Although the duration of the release period of CRF Polyon 12 under the 1995 experimental conditions was much shorter than the crop duration in the WS_{TL} and WS_{PI} treatments (127 and 122 days; Table 2), crop performance was similar to that in the PU treatment. We postulate that the lack of agreement between the present study and that of Tuong *et al.* (2002) could be ascribed to differences in the soil types in the two studies. The lighter soil in the present study might have induced a higher percolation rate and, therefore, a larger nitrate N loss because of leaching, particularly when N was applied as PU and under stress conditions. This loss may exert the same effect as the unavailability of N from CRF Polyon 12 at the end of its release period.

Effect of N rate

In general, in the 1994 experiment, the rate of total dry matter accumulation (presented by the slope of the

Table 6 Grain yield, straw yield, total dry matter accumulation, filled spikelets, 1000-grain weight and harvest index of PSBRc14 as affected by water treatment (1995 dry season)

Water[†]	Grain yield ($t\ ha^{-1}$)	Straw yield ($t\ ha^{-1}$)	Total dry matter accumulation ($t\ ha^{-1}$)	Filled spikelets (%)	1000-grain weight (g)	HI[§]
WW	5.4 a[‡]	6.0 ab	11.5 a	86.6 a	19.4 a	0.45 a
WS_{TL}	4.8 a	5.0 bc	9.9 a	79.9 a	17.7 b	0.46 a
WS_{PI}	3.0 b	4.3 c	7.2 b	82.4 a	15.9 c	0.38 b
WS_{GF}	3.3 b	7.1 a	10.4 a	68.8 b	17.8 b	0.29 c

[†] Means are the average over two fertilizer sources. WW, well-watered plants; WS_{TL}, stress at the tillering stage; WS_{PI}, stress at the panicle initiation stage; WS_{GF}, stress at the grain-filling stage. [‡] In each column means followed by the same letter are not significantly different at the 5% level using Duncan Multiple Range Test (DMRT). [§] Harvest index (HI) = grain yield for oven-dry moisture content/total dry matter.

time-course calculated from the data in Fig. 4) in the absence of N application (N_0) was lower than that in the treatments with higher N rates (Fig. 4a vs Fig. 4b,c,d). There was no clear difference in the rate of total dry matter accumulation between N_{60} and the treatments with higher fertilizer rates (Fig. 4b vs Fig. 4c,d).

At harvest, total dry matter accumulation and straw yield in N_0 were significantly lower ($P < 0.05$) than those in the other fertilizer treatments, irrespective of the water stress treatments (Table 5). Total dry matter accumulation and straw yield in the N_{60}, N_{120} and N_{180} treatments were generally similar. Light soil used in the present study may have induced high percolation losses, preventing the plants from maximizing the use of N applied at more than 60 kg N ha^{-1}. The absence of significant differences among the applied N treatments may also indicate that plant growth and yield were limited by other factors (such as high rainfall during flowering, Fig. 1, which may affect the pollination process). Grain yield in N_0 was significantly lower than that in the fertilized treatments, except when the crop was stressed at the flowering stage, and in N_{60} when the crop was stressed during the grain-filling stage. As a result of the increased straw yield and the decreasing trend of grain yield with N rate, HI in the WS_{FL} treatment decreased significantly with increasing N rate. Our findings differed from those of Khonthasuvon *et al.* (1998) and Boling *et al.* (2004) who did not detect any significant water/N interaction effect on rice yield and reported that the application of N increased the rice yield, even when the plants were water stressed. The stress timing in their studies probably did not coincide with the flowering stage, or the stress level may not have been severe enough to cause the water/N interaction observed in the present study.

Effect of water stress

In both experiments and for all the N rates in 1994, water stress reduced the rate of total dry matter accumulation during the stress periods (Figs 4,5). At the end of the stress period, total dry matter accumulation of the WS_{TL} plants was significantly lower than that of the WW plants (Figs 4,5). The rate of total dry matter accumulation in the WS_{TL} treatment returned to the WW level after the stress period ceased. As a result of the drought-induced delay in maturity (Tables 1,2), the WS_{TL} plants had more time to accumulate dry matter than the WW plants, resulting in the absence of significant differences in the total dry matter accumulation and the straw and grain yields between the WS_{TL} and WW plants in all N treatments at harvest (Tables 5,6).

In 1994, water stress at the flowering stage did not prolong crop duration as observed under the WS_{TL} treatment (Table 1) and this did not allow the crop to compensate for the reduced dry matter accumulation during the stress period, resulting in a significantly lower total dry matter accumulation at harvest in the WS_{FL} than in the WW and WS_{TL} plants. The reduction in the total dry matter accumulation of the WS_{FL} plants mainly resulted from the reduction in grain yield. This was expected because assimilates during the flowering stage are mainly translocated to the storage organs (Kropff *et al.* 1994).

The plants subjected to the WS_{PI} treatment in 1995 showed a lower final biomass and lower straw and grain yields than the WW plants (Table 6). The delay in flowering in the WS_{PI} treatment (Table 2) allowed the stressed crop to partly compensate for the lower increase in straw weight during the stress period.

The stress level in the WS_{FL} treatment in 1994 was less severe than that in the WS_{TL} treatment (Fig. 2), but the WS_{FL} treatment significantly reduced the total dry matter and grain yield of the plants compared with those of the WW plants, unlike the WS_{TL} treatment. Similar results were observed for the WS_{PI} and WS_{TL} treatments in 1995. The stress level in the WS_{FL} treatment in 1994 was less severe than that in the WS_{PI} treatment in 1995. However, the percentage of yield reduction in the WS_{FL} plants compared with that in the WW plants in 1994 was higher than that in the WS_{PI} plants in 1995. The results confirmed earlier findings

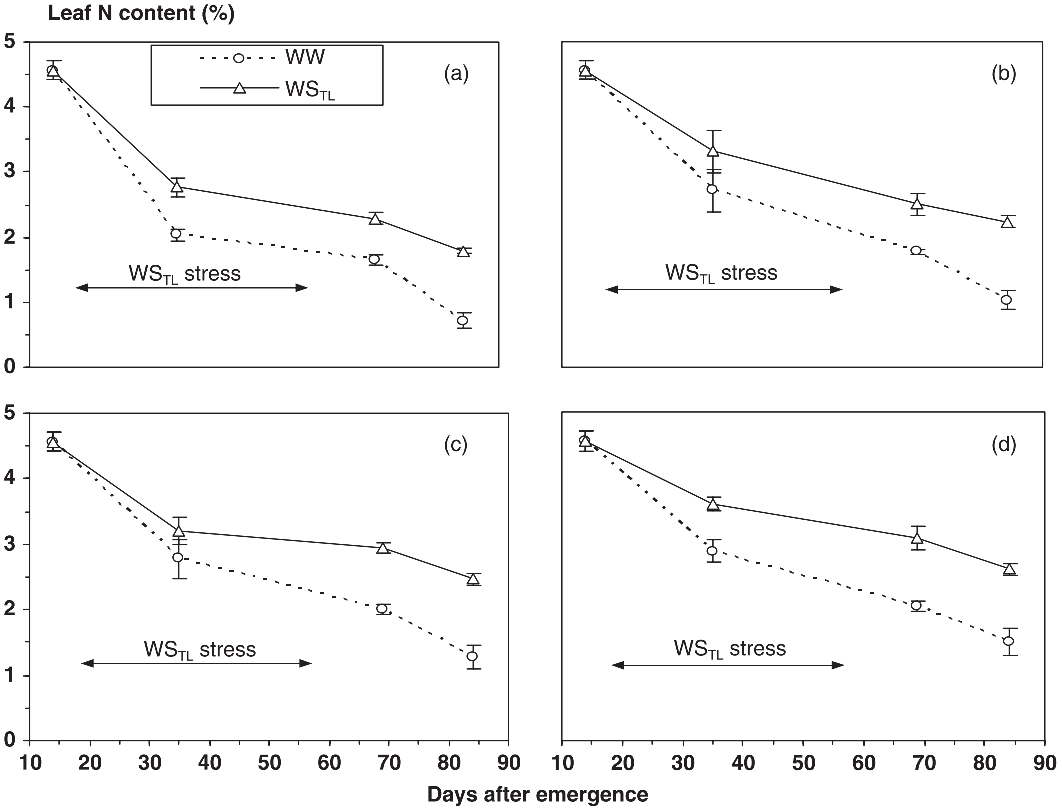

Figure 6 Leaf N content of IR72 at (a) 0, (b) 60, (c) 120 and (d) 180 kg N ha^{-1} as affected by water stress at the maximum tillering stage (WS_{TL}). Mean ± standard error. Data were averaged over two N sources and four replications. WW, well-watered plants.

showing that water stress at the FL stage is more detrimental to yield, followed by stress at the PI stage, whereas stress at the vegetative stage does not affect grain yield significantly (Castillo *et al.* 1992; Wopereis *et al.* 1996; Yambao and Ingram 1988). Most of the previous studies, however, were carried out with transplanted rice.

Water stress imposed on the plant at the GF stage did not significantly change either the rate of total dry matter accumulation during the stress period (Figs 4,5), the straw yield or the final total dry matter accumulation compared with the WW plants (Tables 5,6). Grain yield was reduced compared with that in the WW plants in 1995, but not in 1994. The difference between the 2 years was attributed to the severe stress level in 1995. The reduced yield in the 1995-WS_{GF} plants could be attributed to the short grain-filling period that was brought about by accelerated senescence because of severe water stress. This is consistent with the decrease in the percentage of filled spikelets and the low value of the 1000-grain weight (Table 6). O'Toole and Chang (1979) also observed that drought during the grain-filling stage resulted in a lower value of the grain weight, and Boonjung and Fukai (1996) reported a 20% reduction in grain mass compared with well-watered plants when stress occurred during the late rice grain-filling stage.

Nitrogen content and uptake

Figure 6 shows a comparison of the leaf-N concentration of the rice cv IR72 between the WW and WS_{TL} treatments for different N rates in 1994. Corresponding data for culm-N concentration are shown in Fig. 7. In general, the leaf-N concentration tended to increase as the N rate increased from 0–60 to 120 kg ha^{-1}. A similar trend was observed for the culm-N concentration when the N-application rates increased from 0 to 60 kg ha^{-1}, but without further increase at higher N rates.

Across all the N treatments, the mean leaf-N and culm-N concentrations (Figs 6,7) of the WS_{TL} plants during and after the stress period (until the FL stage) were significantly higher than those in the well-watered plants. Similar results were observed for the WS_{TL} and WS_{PI} plants in 1995 (data not shown).

The higher N concentration in the stressed plants suggests that water stress limited growth more than N transport to the plants. This is supported by the findings of Hsiao (1973) who reported that the first effect of drought is the restriction of cell enlargement. Higher N concentration in the stressed plants could also be attributed to a lower "dilution" because of restricted growth.

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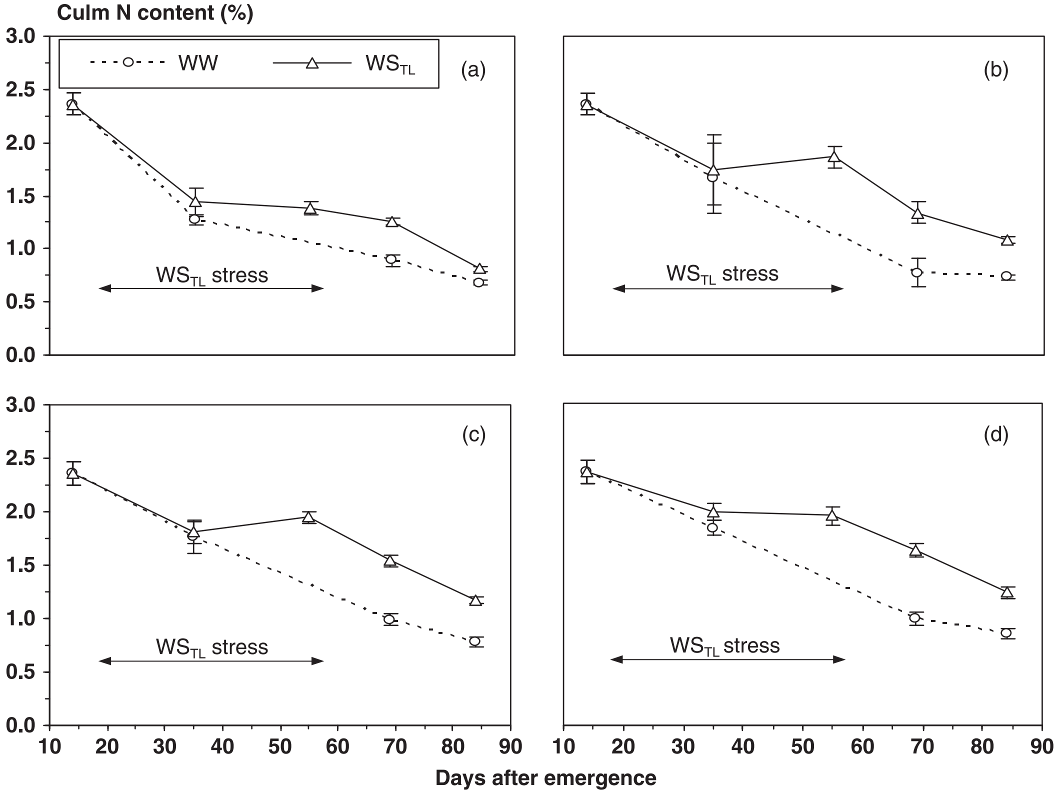

Figure 7 Culm N content of IR72 at (a) 0, (b) 60, (c) 120 and (d) 180 kg N ha^{-1} as affected by water stress at the maximum tillering stage (WS_{TL}). Mean ± standard error. Data were averaged over two N sources and four replications. WW, well-watered plants.

At maturity, straw-N, grain-N and total-N uptake generally increased with increasing N rate. However, because of the strong water/N-rate interaction, the increases and their significance varied with the water treatments (Table 7). Straw and total N uptake in N_0 were invariably lower than that in the N application treatments. Treatments N_{120} and N_{180} led to significantly higher straw and total-N uptake than N_{60}, except for the WS_{TL} treatment in which the uptake was similar. Different N-rate treatments did not result in significant differences in grain-N uptake in the WS_{TL} and WS_{FL} plants, but treatments with higher N rates (N_{120} and N_{180}) led to a significantly higher grain-N uptake in the WW and WS_{GF} plants.

Among the water treatments, straw-N uptake in the treatments with lower N rates (0 and 60 kg ha^{-1}) did not differ (Table 7). In the N_{120} and N_{180} treatments, the uptake was lowest in the WS_{TL} and highest in the WS_{FL} treatments. Grain total-N uptake was always lowest in the WS_{FL} treatment irrespective of the N-rate treatments, which is related to the lowest yield of the WS_{FL} plants (Table 5).

Nitrogen-use efficiency

The PEN value decreased as the N rate increased (Table 8). The PEN value in N_0, which was significantly higher in the WS_{FL} and WS_{GF} plants, was comparable with that in N_{60} in the WW and WS_{TL} plants. Water stress during the tillering and grain-filling stages did not affect the PEN value, while WS_{FL} significantly reduced the PEN value compared with all the other water treatments. This implies that the WS_{FL} treatment reduced the grain yield more than the total N uptake and that there was a low translocation of N from straw to grain, as evidenced by the high proportion of straw biomass compared with grain yield. There was a significant water/N-rate interaction on AEN, such that increasing the N rate did not affect AEN under the WS_{FL} and WS_{GF} treatments but reduced it under the WW and WS_{TL} treatments (Table 8). Among the water treatments, the AEN value was zero for all N rates under the WS_{FL} treatment, because additional N did not increase the grain yield in the WS_{FL} plants (Table 5). As the differences in the grain-N concentration among the water treatments were relatively small compared with the differences in the grain yield (Table 7 vs Table 5), trends in the total grain-N uptake, PEN and AEN values among the water treatments were strongly influenced by the grain yield.

There were non-significant differences in the REN values among the N rates in all water regimes. The REN

Table 7 Plant-N uptake of IR72 as affected by water and fertilizer treatments and their interaction (1994 dry season)

	Water treatments†							
N Treatment†	WW	WS_{TL}	WS_{FL}	WS_{GF}	WW	WS_{TL}	WS_{FL}	WS_{GF}
(NR)†		Straw N concentration (%)				Straw N uptake (kg ha^{-1})		
0	0.7 b‡	0.7 b	0.9 d	0.7 b	23 c	26 b	29 d	22 c
60	0.7 b	0.8 a	1.0 c	0.8 b	36 b	44 a	48 c	39 b
120	1.0 a	0.9 a	1.2 b	0.9 a	56 a	48 a	69 b	53 a
180	1.0 a	0.8 a	1.3 a	0.9 a	61 a	45 a	83 a	57 a
§$LSD_{0.05}$	0.14				12			
		Grain N concentration (%)				Grain N uptake (kg ha^{-1})		
0	1.2 c	1.4 a	1.6 b	1.2 c	30 c	51 a	16 a	38 b
60	1.3 bc	1.4 a	1.9 a	1.3 bc	52 b	67 a	17 a	41 b
120	1.2 ab	1.3 a	1.6 b	1.5 ab	67 a	61 a	14 a	67 a
180	1.6 ab	1.3 a	1.5 b	1.6 a	68 a	57 a	5 a	79 a
§$LSD_{0.05}$	0.20				26			
						Total N uptake (kg ha^{-1})		
0					53 c	77 b	45 c	60 c
60					88 b	110 a	65 b	80 b
120					123 a	109 a	83 ab	120 a
180					129 a	102 a	88 a	136 a
§$LSD_{0.05}$					24			

†Means are the average over two fertilizer sources. WW, well-watered plants; WS_{TL}, stress at the tillering stage; WS_{PI}, stress at the panicle initiation stage; WS_{GF}, stress at the grain-filling stage. ‡In each column, means followed by the same letter (a, b, c) are not significantly different at the 5% level using Duncan Multiple Range Test (DMRT). §Least significant difference ($LSD_{0.05}$) was used to compare two W means at each NR.

Table 8 Nitrogen-use efficiency parameters of IR72 as affected by water and fertilizer treatments and their interaction (1994 dry season)

	PEN¶ (kg grain kg N uptake^{-1})				AEN†† (kg grain kg N applied^{-1})				REN‡‡ (%)			
Treatment	WW	WS_{TL}	WS_{FL}	WS_{GF}	WW	WS_{TL}	WS_{FL}	WS_{GF}	WW	WS_{TL}	WS_{FL}	WS_{GF}
Nitrogen rate (NR)†												
0	45 a‡	44 a	22 a	49 a	–	–	–	–	–	–	–	–
60	43 a	40 ab	13 b	38 b	22 a	19 a	0 a	4 a	58 a	35 a	34 a	33 a
120	34 b	39 ab	9 b	37 b	15 ab	7 b	0 a	12 a	58 a	28 a	32 a	50 a
180	31 b	37 b	3 c	34 b	8 b	3 b	0 a	10 a	42 a	14 a	24 a	42 a
§$LSD_{0.05}$		10				12				24		

†Means are the average over two fertilizer sources. ‡In each column, means followed by the same letter (a, b, c) are not significantly different at the 5% level using Duncan Multiple Range Test (DMRT). §Least significant difference ($LSD_{0.05}$) was used to compare two W means at each NR. ¶PEN = physiological N-use efficiency (kg grain kg N uptake^{-1}) = grain yield*0.86/total plant N uptake. ††AEN = agronomic N-use efficiency (kg grain kg N applied^{-1}) = grain yield$_{fertilized}$ – grain yield$_{control}$*0.86/N applied. ‡‡REN = apparent recovery of applied N (%) = total N uptake$_{fertilized}$ – total N uptake$_{control}$/fertilizer N applied × 100.

values in the WW and WS_{GF} treatments were similar and significantly higher than those in the WS_{FL} and WS_{TL} treatments (Table 8). Lower REN values in the WS_{TL} and WS_{FL} treatments imply that water stress increased N loss through denitrification and leaching because of drying and wetting, compared with those in the WW plants. Thus, water stress may not only reduce the yield but may also exacerbate environmental pollution.

Conclusions

The present study revealed that the effects of stress timing on crop development, crop growth and yield of DS rice were similar to those on TP rice. Stress during the vegetative and PI stages delayed anthesis and maturity. Stress at the FL stage was most detrimental to yield, followed by stress at the PI stage, while stress at the vegetative stage did not affect grain yield. Stress at the grain-filling stage reduced the grain yield and accelerated senescence only when the stress was severe. Water stress management for DS rice can benefit from the experience gained in the stress management of TP rice.

The CRFs in the present study did not offer any advantage over PU (four applications). Taking into account the low availability and cost of the CRFs, multiple-split

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applications of PU remain a better option than the use of CRFs for farmers in rainfed lowland areas.

The results highlighted the effects of water and N fertilizer and their interaction on grain yield. While the application of N increased the yield despite drought stress at the MT, PI and GF stages, it did not increase the yield of DS rice when stress occurred at the FL stage. The significantly lower PEN value under the WS_{FL} treatment (compared with the other water treatments) indicated that, when stressed at the FL stage, the rice plants could not translocate the absorbed N into the grains. This could be attributed to the increased pollen sterility (evidenced by the increase in the proportion of unfilled spikelets [data not shown]) and reduced sink size, which could not accommodate the translocated carbon from the leaves as in the control plot. Drought at the FL stage increased the farmer's risk of lower returns when a large amount of N fertilizer was applied at the early stages of crop growth. This suggests that, while rainfed rice farmers should apply an adequate amount of fertilizer to ensure satisfactory vegetative growth, they should delay the last N application as much as possible before heading, at which time they may then have a better knowledge of the likely worst-case field water conditions during the FL stage to decide whether it is worth the risk of applying a larger amount of fertilizer.

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