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The drought response of lowland rice to crop establishment practices and N-fertilizer sources

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Abstract

Increasing drought resistance and nutrient availability to the plant is important for increasing yields in rainfed lowland rice. This study investigated the effects of crop establishment and controlled-release fertilizers on drought stress responses and nitrogen uptake of rice (*Oryza sativa* L.) cv. PSBRc14 grown on a clayey loam Vertic Tropaquept in a split-split-plot field experiment. The main plots were two water treatments (well-watered and drought-stressed for 20 days from panicle initiation). The subplots comprised of three crop establishment methods. In the sub-subplots, prilled urea was compared with Polyon 12 and POC-S120. Drought prolonged crop maturity by about 20 days and greatly reduced grain yield but not the total biomass and total N uptake. Dry-seeded rice had a lower yield in the well-watered treatment but higher yield in the stress treatment compared with transplanted and wet-seeded rice. The higher yield of dry-seeded rice under stress could be related to its significantly higher root length density, higher root–shoot ratio, and more uniform root distribution with respect to soil depth, and higher available soil moisture in the root zone during the stress period. Under the well-watered condition, yields in all fertilizer treatments were comparable. In the stress treatment, Polyon 12 produced the lowest yield probably because of the mismatch between drought-induced prolongation of crop duration and the release period of Polyon 12.

Keywords: Direct-seeded rice; Controlled-release fertilizer; Soil physical properties; Water stress

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1. Introduction

The relatively low yield of rainfed lowland rice may be partly attributed to drought stress (O'Toole and De Datta, 1986; Widawsky and O'Toole, 1990) and nutrient stress, especially N deficiencies (Ponnamperuma and Ikehashi, 1979). Rainfed lowland rice is often transplanted (TP), but because of the labor scarcity in the last decade, many farmers have changed from transplanting to direct seeding of rice. In direct wet seeding (WS), pre-germinated seeds are broadcast onto puddled soils in direct dry seeding (DS), seeds are sown onto dry or moist non-puddled soils.

Most research on lowland rice response to drought stress has been carried out on TP rice (Aragon et al., 1987; Yambao and Ingram, 1988; Castillo et al., 1992). We hypothesized that crop establishment methods strongly influence lowland rice response to drought stress. Crop establishment methods affect root length density and distribution (Naklang et al., 1996). Soil conditions (puddled in WS and TP rice and

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non-puddled in DS rice) also affect the water-release characteristics of the soil during the stress period. These, in turn, may have a profound influence on the water extraction pattern and crop response when the plant is subjected to water deficit.

A unique feature of rainfed systems is the alteration between aerobic and anaerobic soil conditions, which promotes nitrification and subsequent uptake and/or loss of N because of leaching and denitrification. The key to both improving efficiency of fertilizer use and reducing N losses is synchronization of N supply from soil with plant demand for N. One possible approach is the use of controlled-release fertilizers (CRFs) that have an ultra-thin membrane polymer coating that encapsulates a urea granule. The release of nutrients through the membrane of CRF occurs in a predictable manner, which is almost independent of the soil moisture regime (Gandeza and Shoji, 1992). Given the growth duration of a rice crop, it is possible to match urea release from CRF with the anticipated N demand by selecting the appropriate polymer membrane coating. Singh et al. (1995) reported that grain yield under irrigated conditions from a single application of CRF was equivalent to or better than 3–4-split N applications. Trebuil et al. (1998) also reported that one application of CRF increased N use efficiency compared with three split applications of urea in drought-prone rainfed rice in northeast Thailand. In contrast, Wade et al. (1999) found an inconsistent response of rainfed lowland rice to CRFs. Furthermore, CRFs are costly and not readily available for most farmers in rainfed systems. It is important to investigate other N-fertilizer management practices that enhance the synchronization of N supply with plant demand for N. We postulated that multiple split N application at critical growth stages could be as effective as CRFs in drought-prone rainfed systems. It is also possible that different crop establishment methods, which may modify root growth, root distribution, and water uptake, will also influence the root-zone nutrient availability and plant uptake of different forms of fertilizer.

This study was carried out to test the above hypotheses. It compared the drought stress responses and nitrogen uptake of DS, WS and TP rice cv. PSBRc14 when it was fertilized with split applications of prilled urea (PU) and CRFs.

2. Materials and methods

2.1. Experimental site

The experiment was conducted at the International Rice Research Institute (IRRI), Los Baños, Philippines (14°30′N, 121°1′E) from February to June 1995. According to USDA classification (Soil Survey Staff, 1992), the experimental soil is a clayey loam Vertic Tropaquept, with 1.16% organic carbon, 50 kg ha^{-1} of KCl extractable $NH_4{}^+$-N and 15 kg ha^{-1} of $NO_3{}^+$ -N ha^{-1}. The total amount of rainfall during the duration of the experiment was 365 mm, most of which fell during May and June. The mean air temperature during the experimental period was 28.1 °C and the average maximum temperature was 33.2 °C.

2.2. Experimental design and cultural practices

The experiment was conducted in a randomized split-split-plot design with three replications. The main plots were two water (W) treatments: well-watered and drought stress for 20 days from panicle initiation (PI) stage. The main plots were hydraulically isolated by plastic sheets installed to 0.6 m depth. In the subplots, rice cv. PSBRc14 was established by DS, WS and transplanting. The sub-subplots (5 m × 4 m) and consisted of three fertilizer sources: conventional PU and two controlled-release urea fertilizers, Polyon 12 and POC-S120.

All fields were plowed with a tractor and harrowed three times in a dry condition to about 15 cm depth. About 13 kg P ha^{-1}, 25 kg K ha^{-1} and 4.5 kg Zn ha^{-1} were incorporated during the final harrowing. On 13 February, 100 kg ha^{-1} seeds were manually sown at 1–2 cm depth on dry soil and at a 20 cm row spacing in the DS plots. The plots were flush-irrigated daily until the crop was fully established.

On the same day of the first flush irrigation of the DS plots, seeds were soaked for the preparation of WS and TP rice. All WS and TP plots were flooded and harrowed under saturated moisture to puddle the soil to a depth of 10 cm. The pre-germinated seeds were sown in the WS plots on 16 February at the same rate and row spacing as DS rice. At the same time, part of the pre-germinated seeds were grown in seedling trays. Seedlings were TP 15 days later at a spacing of 20 cm × 20 cm.

The established plant density of DS and WS rice was about 55–60 plants per linear meter row (275–300 plants m^{-2}). After crop establishment, all plots were flooded to about 5 cm water depth. In the drought treatment, water was drained at the start of PI (15 April) and irrigation was withheld for 20 days. A negligible amount of rainfall (1.2 mm) fell during the stress period. At the end of the stress, most plants showed signs of severe stress with fully rolled leaves.

In all fertilizer treatments, N was applied at a rate of 80 kg N ha^{-1}. PU was applied in four equal splits (basal, maximum tillering, PI and flowering). In the drought stress treatment, to avoid drought-induced N losses, the second PU top dressing (supposedly at PI) was delayed until the stress had been relieved (Table 1). The slow-release fertilizers were incorporated into the soil at 1–2 cm depth in one single dose at the time of seeding in DS and WS rice. In TP rice, they were placed in the soil of the seedling tray.

2.3. Soil property monitoring

Soil samples for 0–5, 5–10 and 10–20 cm depths were taken on the first day of the stress for the determination of water retention characteristics of the puddled (for WS and TP rice) and non-puddled (for DS rice) soils, using the pressure membrane method. During the stress imposition, soil water potentials at the above depths were monitored daily, using mercury manometers and tensiometers. When the soil dried out to a point at which soil potentials fell below the air entry value of the tensiometers, soil moisture content was monitored at 2–3-day intervals, using 100 cm^3 cylinders, following the core method (Blake and Hartge, 1986). Soil penetration resistance was measured in all stressed plots (four measurements per plot) using the Bush Recording Penetrometer at 2–3-day intervals.

2.4. Plant sampling and N uptake

Periodic harvestings of 12 hills from each TP plot and four rows of 0.5 linear meter from each DS and WS plot were made at critical growth stages and during the stress period (Table 1). At physiological maturity, rice plants from the designated 5 m^2 areas were cut to ground level. Yield components were determined from the sampling quadrants at four corners of the harvest area. Straw (all, except spikelets, above-ground components of the rice plant) and grain dry weight were determined for each sampling. Subsamples of straw and grain were ground by a Beater Cross grinder and were subjected to N analysis. Total N in straw and grain was calculated from grain and straw dry matter and their respective N contents.

Table 1
Timing of stress imposition, top dressing of PU, plant sampling and phenological development of the crop

Events	Date (and days after emergence[a])								
	30 March (38)	10 April (49)	15 April (54)	20 April (59)	27 April (66)	4 May (73)	11 May (80)	3 June (103)	23 June (123)
Well-watered									
Crop stage		PI[b]				FL[c]		Har[c]	
PU top dressing	1st	2nd				3rd			
Crop sampling	1st	2nd		3rd	4th	5th		6th	
Stress									
Stress			Start			End			
Crop stage		PI[b]					FL[d]		Har[d]
PU top dressing	1st					2nd	3rd		
Crop sampling	1st	2nd		3rd	4th	5th	6th		7th

[a] Emergence of the DS and WS rice.

[b] PI varied from 9 to 12 April.

[c] FL, flowering varied from 2 to 5 May and Har, harvest from 2 to 5 June.

[d] Flowering varied from 8 to 15 May and harvest from 22 to 24 June.

2.5. Root measurements

Root samples were taken at the flowering stage (4 May) in the well-watered plots, at 5 days after the stress imposition (20 April), and at the flowering stage (11 May) in the stressed plots, using a 45 cm long, 10 cm diameter steel cylinder. In TP rice, the sampled rice hill was at the center of the cylinder. In WS and DS rice, the sampler was placed over a rice row to sample 5 or 6 plants (within the 10 cm linear length of cylinder diameter). The cylinder was driven by a hydraulic jack and retrieved by a pulley assembly. The soil was divided into layers corresponding to 0–5, 5–10, 10–20 and 20–40 cm depths. The roots were washed, cleaned and scanned using a COMAIR scanner (Commonwealth Aircraft, Melbourne, Australia). They were dried and their dry weights were recorded. Root–shoot ratios were calculated from root dry weights and the above-ground biomass.

2.6. Data analysis

Soil, crop and nitrogen data were analyzed with standard split-split-plot analysis of variance techniques. When there were no three- and two-way interactions among water, crop establishment and fertilizer source treatments the reported data for different crop establishment methods were pooled across the three fertilizer sources and vice versa.

3. Results

3.1. Soil moisture and soil penetration resistance

Fig. 1 shows that puddling modified the water retention characteristic curve of the soil considerably. The soil moisture content at the permanent wilting point (corresponding to soil matric potential $= -1500$ kPa) of the puddled topsoil layers was significantly higher than that of the non-puddled soil. Puddling also increased the saturated soil moisture of the 0–5 cm layer compared with the non-puddled soil.

After drought stress imposition, soil moisture content in the 0–5 and 5–10 cm layers of the three crop establishment methods decreased at about the same rate (Fig. 2a and b). Soil moisture in the WS and TP rice, however, reached the permanent wilting point before it did in DS rice. At the end of the stress period, soil moisture in the 5–10 cm layer of the DS treatment was still higher than the permanent wilting point (Fig. 2b). From 4 to 13 days after the start of the stress, DS rice had lower soil moisture in the 10–20 cm layer compared with TP (though not significant) and WS rice (Fig. 2c).

At all depths, penetration resistance increased with duration of stress (Fig. 3). At 3 and 10 cm depths, the differences in soil penetration resistance among the crop establishment methods also tended to increase with the stress duration. From 8 days after the start of

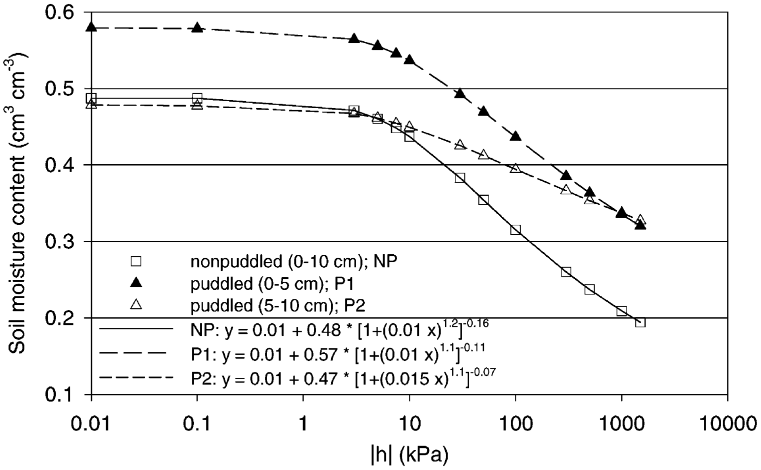

Fig. 1. Soil moisture characteristic curves of non-puddled soil (0–10 cm depth) in DS rice fields and puddled soil (0–5 and 5–10 cm depths) in WS and TP rice fields. h the matric potential.

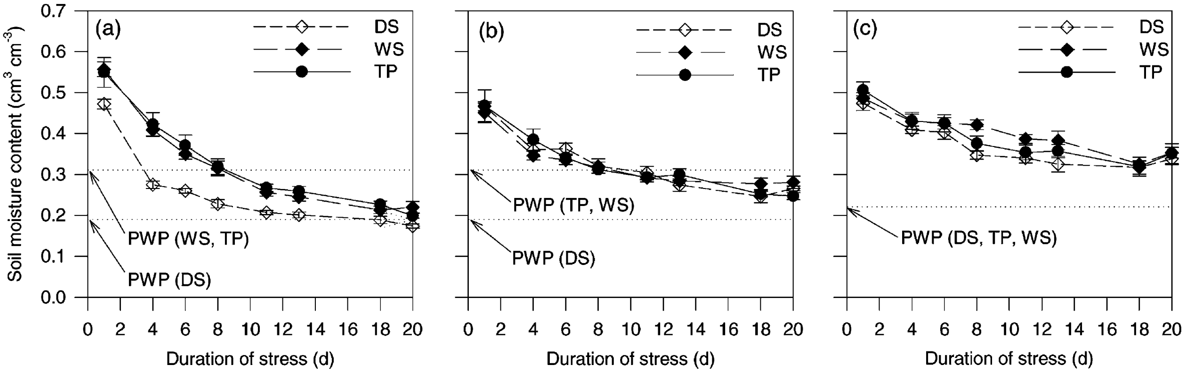

Fig. 2. Soil moisture content at: (a) 0–5, (b) 5–10 and (c) 10–20 cm depths. Vertical bars indicate ±standard errors, $n = 9$. WS, wet-seeded rice; DS, dry-seeded rice; TP, transplanted rice; PWP, permanent wilting point.

the stress, penetration resistance at 10 cm depth in DS treatment became significantly less than that in the other two crop establishment methods (Fig. 3b). At 17 cm depth, soil penetration resistance in DS rice was significantly lower than in WS and TP rice until about 9 days after stress imposition (Fig. 3c).

3.2. Root characteristics

Table 2 shows that root length density generally decreased with depth. In the well-watered treatment sampled at flowering, root length density at all depths of TP rice was significantly lower than that of WS and DS rice. Root length density of WS and DS rice was comparable in the 5 cm topsoil. But at lower depths, root length density of DS rice was higher (though not significant at $P < 0.05$) than that of WS rice. The root–shoot ratio of DS and WS rice was significantly higher than that of TP rice.

Under stress, root length densities at depths of <20 cm of DS rice at 5 days after the start of the stress period were significantly higher ($P < 0.05$) than those of WS and TP rice. The root–shoot ratio of DS rice was higher than that of WS rice (not significant at the 5% level) and TP rice (significant at the 5% level). At the flowering stage of the stressed plants (1 week after the end of the stress period), differences in root length densities among crop establishment methods had the same trend as those of the well-watered plants, but the difference in root length densities at depths of 5–20 cm between DS and WS rice was now significant at the 5% level.

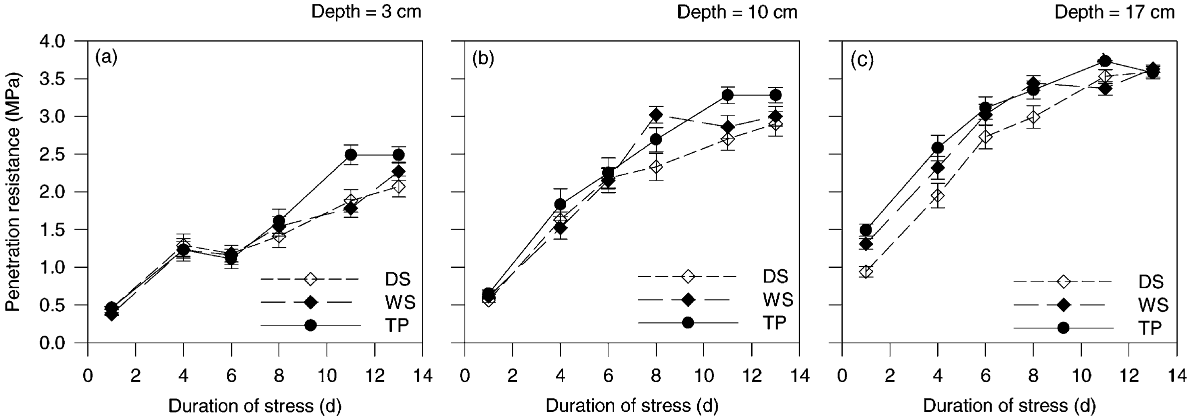

Fig. 3. Soil penetration resistance at different soil depths during the stress period. Vertical bars indicate ±standard errors, $n = 9$. WS, wet-seeded rice; DS, dry-seeded rice; TP, transplanted rice.

Table 2
Root length density and root–shoot ratio of DS, WS and TP rice under well-watered and stress treatments

Depth (cm)	DS	WS	TP
Well-watered			
Sampled at flowering (4 May)			
Root length density (km m^{-3})			
0–5	458 ab[a]	563 a	303 b
5–10	140 a	94 a	83 b
10–20	40 a	28 ab	14 b
20–40	7 a	6 ab	4 b
Root–shoot ratio			
	0.049 a	0.046 a	0.034 b
Stress[b]			
Sampled at 5 days after start of stress (20 April)			
Root length density (km m^{-3})			
0–5	221 a	218 b	103 b
5–10	104 a	61 b	55 b
10–20	34 a	18 b	19 b
20–40	8 a	6 ab	5 b
Root–shoot ratio			
	0.081 a	0.061 ab	0.05 b
Sampled at flowering (11 May)			
Root length density (km m^{-3})			
0–5	536 a	468 ab	354 b
5–10	129 a	82 b	75 b
10–20	38 a	18 b	21 b
20–40	9 a	9 a	8 a
Root–shoot ratio			
	0.058 a	0.054 a	0.056 a

[a] In the same row, treatment means followed by a common letter are not significantly different at 5% level by DMRT.

[b] Stress period is from 15 April to 4 May 1995.

3.3. Crop development, tiller number, straw weight and biomass

The drought stress delayed flowering of the stressed plants about 7–10 days and the harvest about 20 days compared with the well-watered plants (Table 1). At the end of the stress imposition period, the stressed plants approached the heading stage while the well-watered plants already reached the flowering stage.

Fig. 4 shows the time course of tiller number of the rice crops. After maximum tillering, the number of tillers in the well-watered treatment of all crop establishment methods decreased until harvest. In the stress treatment, tiller number declined during the stress period but increased again after the stress was relieved. The final tiller number of the stress treatment was significantly higher than that in the well-watered treatment in all crop establishment methods.

Fig. 5 compares straw weight and biomass of DS, WS and TP rice under well-watered and stress conditions. The corresponding data are presented for different sources of nitrogen fertilizer in Fig. 6. During the stress period, irrespective of crop establishment methods and fertilizer sources, the mean growth rate (Table 3) and the rate of straw weight accumulation (data not shown) of the stressed plants were significantly lower than those of the well-watered plants. At the end of the stress period, the mean straw weight under the stress treatment was about 80% of that under the well-watered treatment (Fig. 5a vs. b and Fig. 6a vs. b). The corresponding value for biomass was 70% (Fig. 5c vs. d and Fig. 6c vs. d).

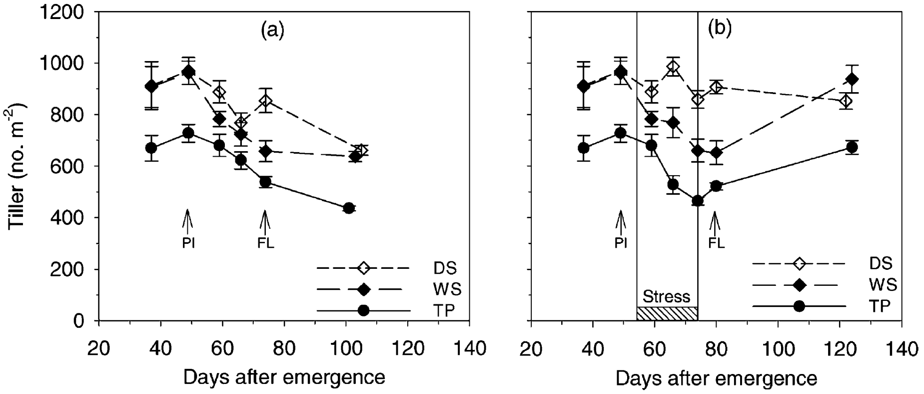

Fig. 4. Tiller numbers of rice cv. PSBRc14 under: (a) well-watered and (b) drought stress conditions. The hatched bar indicates the drought stress duration. Vertical bars indicate ±standard errors, $n = 9$. PI, panicle initiation; FL, flowering.

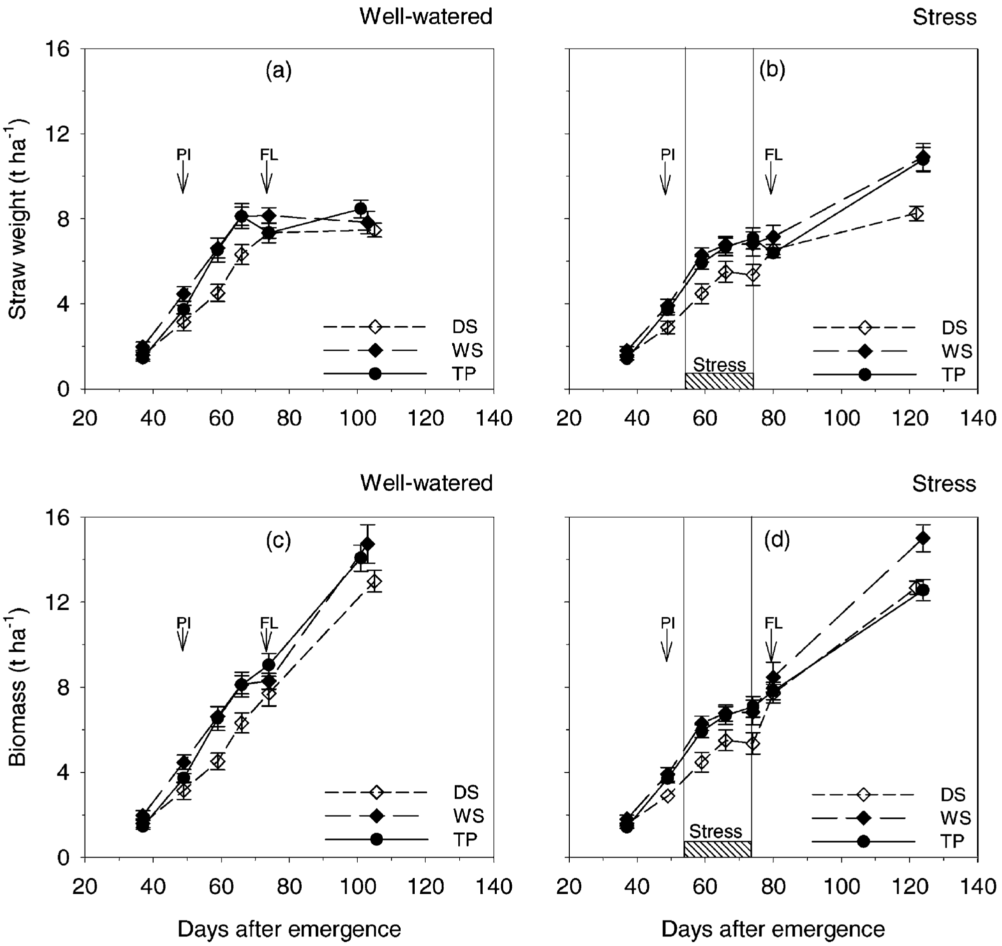

Fig. 5. Straw dry weight (a) and (b) and total biomass (c) and (d) of rice cv. PSBRc14 as affected by water regimes and crop establishment methods. WS, wet-seeding; DS, dry-seeding; TP, transplanting. The hatched bar indicates the drought stress duration. Vertical bars indicate ±standard errors, $n = 9$. PI, panicle initiation; FL, flowering.

The straw weight under the well-watered treatment changed only slightly from flowering to harvest (Figs. 5a and 6a). The straw weight under the stress treatment increased at an average of about 71 kg ha^{-1} day^{-1} (derived from Figs. 5b and 6b) in the same period, resulting in significantly higher straw weight at harvest under the stress treatment compared with the well-watered treatment.

From stress relief until harvest, the mean growth rate of the stressed plants was lower (not significant) than that of the well-watered plants (Table 3). But there was no significant difference in the mean biomass between the stress and the well-watered treatments at harvest (Fig. 5c vs. d and Fig. 6c vs. d). This was attributed to the delay in the harvest of the stress treatment (Table 1) allowing more time for the stressed plants to accumulate biomass compared with the well-watered plants.

Among the crop establishment methods, DS rice had a significantly lower straw weight and biomass than WS and TP rice in most of the sampling times before flowering (Fig. 5a–d). At harvest, straw weight was similar in the three crop establishment methods under the well-watered treatment (Fig. 5a). In contrast, the straw weight of DS rice remained lower than that of WS and TP rice in the stressed treatment (Fig. 5b). The final

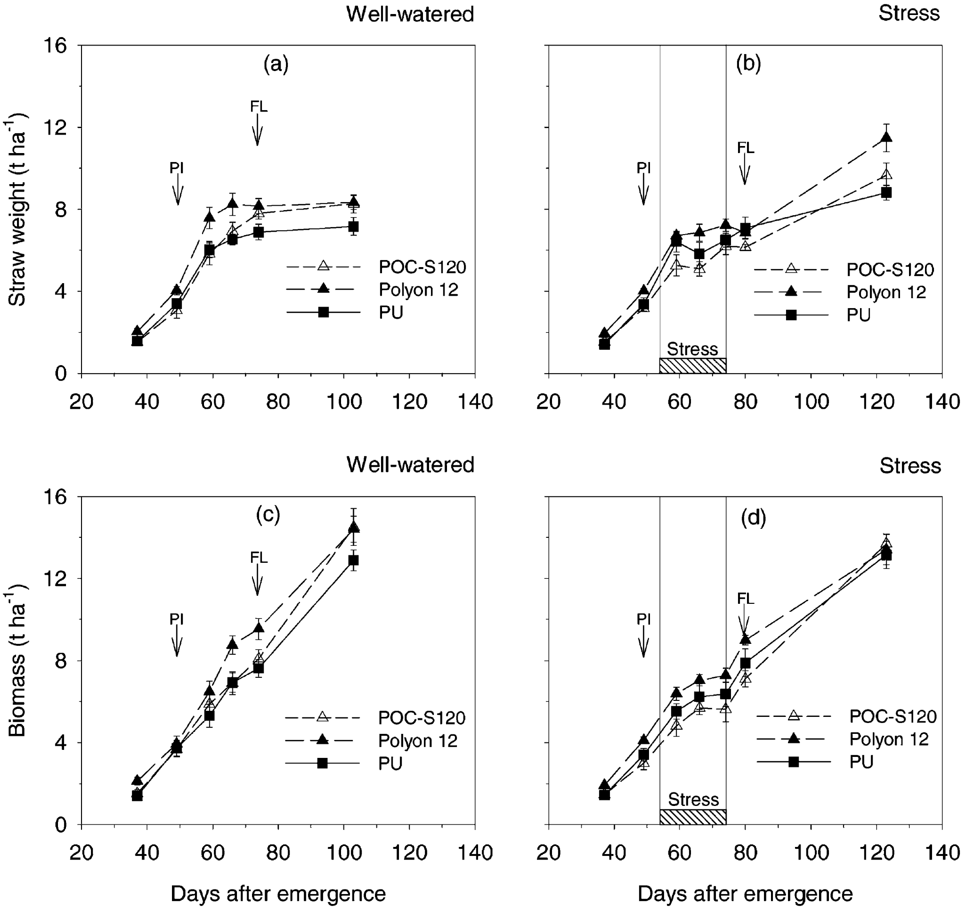

Fig. 6. Straw dry weight (a) and (b) and total biomass (c) and (d) of rice cv. PSBRc14 as affected by water regimes and N-fertilizer sources. The hatched bar indicates the drought stress duration. Vertical bars indicate ±standard errors, $n = 9$. PI, panicle initiation; FL, flowering.

biomass under the well-watered treatment of WS and TP rice was significantly higher than that of DS rice (Fig. 5c), whereas, in the stress treatment, the final biomass of TP and DS rice was about the same and it was lower than the final biomass of WS rice (Fig. 5d).

Fig. 6a–d show that Polyon 12 had a higher straw weight and biomass than the other two fertilizer samples taken before the flowering stage of the crops in both the stress and well-watered conditions. Water by fertilizer interaction had a significant effect on straw weight at harvest, such that straw weight at harvest did not differ significantly among the fertilizer treatments under well-watered conditions (Fig. 6a), but the straw weight at harvest of Polyon 12 was significantly higher than that of PU and POC-S120 under stress conditions (Fig. 6b). After anthesis, the growth rate under Polyon 12 became lower than that of PU and POC-S120 (though significant at 5% only when compared with POC-S120 under well-watered conditions, Table 3), resulting in no significant difference in biomass at harvest among the fertilizer treatments in both well-watered and stress conditions (Fig. 6c and d).

3.4. Nitrogen uptake

Across all treatments, the mean straw N concentration at harvest of the stressed plants was significantly higher ($P < 0.01$) than that of the well-watered plants, but there was no significant difference in the mean grain N concentration between the two water treatments (Table 4). With higher straw yield and straw N

Table 3
Crop growth rate (kg ha^{-1} day^{-1}) between the two samplings on 20 April and 4 May (corresponding to 59–73 days after emergence of the DS and WS crop) and during flowering–harvest as affected by water, fertilizer sources, crop establishment treatments and their interactions. Stress duration was from 15 April to 4 May. In the water stress treatment, flowering occurred about 7 days after rewatering

	20 April–4 May		Flowering–harvest	
	Well-watered	Stress	Well-watered	Stress
Crop establishment (C)[a]				
DS	214 a[b]	58.5 a	181.6 a	170.3 a
WS	110.6 a	34.7 a	222.7 a	190.4 a
Transplanting	180.6 a	76.6 a	166.4 a	127.6 a
Fertilizer source (F)[c]				
PU	154 a	56 a	181.8 ab	158 a
Polyon 12	204.3 a	59.4 a	167.3 b	142.7 a
POC-S120	146.3 a	54.3 a	221.5 a	187.5 a
Mean[d]	168.4	56.6	190.2	162.7
Water effect	**		NS[e]	
C and F interaction	NS		NS	
Water, C and F interaction	NS		NS	

[a] Means are average over three fertilizer sources.

[b] In each column, means followed by the same letter are not significantly different at 5% level by DMRT.

[c] Means are average over three crop establishments.

[d] Means are average across all treatments.

[e] Not significant.

** Significant at 1% level.

Table 4
Straw and grain N concentration, straw, grain and total N uptake as affected by water, fertilizer, crop establishment treatments and their interactions

	N concentration (%)				N uptake (kg ha^{-1})					
	Straw		Grain		Straw		Grain		Total	
	Well-watered	Stress	Well-watered	Stress	Well-watered	Stress	Well-watered	Stress	Well-watered	Stress
Crop establishment (C)[a]										
DS	0.67 b[b]	0.74 b	1.16 ab	1.24 b	50 a	63 c	58 b	48 a	109 b	111 b
WS	0.61 b	0.77 b	1.08 b	1.31 b	51 a	92 b	63 b	38 b	114 b	129 a
Transplanting	0.76 a	1.03 a	1.22 a	1.55 a	62 a	106 a	68 a	33 b	130 a	139 a
Fertilizer source (F)[c]										
PU	0.63 b	0.82 a	1.11 b	1.31 b	45 b	80 a	58 b	40 ab	103 b	120 a
Polyon 12	0.62 b	0.82 a	1.09 b	1.37 b	50 b	86 a	61 b	34 b	112 b	120 a
POC-S120	0.79 a	0.90 a	1.26 a	1.43 a	68 a	94 a	70 a	44 a	138 a	139 a
Mean[d]	0.68	0.85	1.15	1.37	55	87	63	40	118	126
Water effect	**		NS[e]		**		*		NS	
C and F interaction	NS		NS		NS		NS		NS	
Water, C and F interaction	NS		NS		NS		NS		NS	

[a] Means are average over three fertilizer sources.

[b] In each column, means followed by the same letter are not significantly different at 5% level by DMRT.

[c] Means are average over three crop establishments.

[d] Means are average across all treatments.

[e] Not significant.

* Significant at 5% level.

** Significant at 1% level.

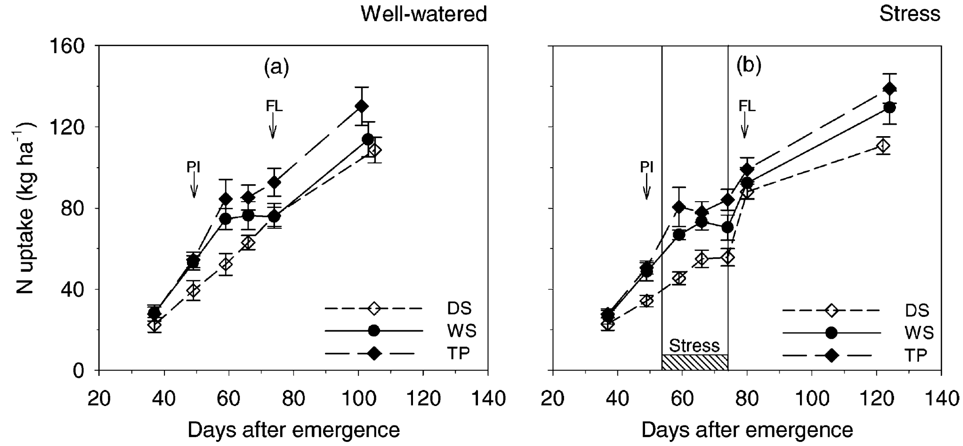

Fig. 7. N uptake of (a) well-watered and (b) stressed rice cv. PSBRc14 as affected by crop establishment methods. WS, wet-seeding; DS, dry-seeding; TP, transplanting. The hatched bar indicates the drought stress duration. Vertical bars indicate ±standard errors, $n = 9$. PI, panicle initiation; FL, flowering.

concentration, straw N uptake at harvest in the stressed treatment was higher ($P < 0.01$) than in the well-watered treatment. In contrast, the mean grain N uptake in stressed plants was lower than in the well-watered plants ($P < 0.05$). There was no significant difference in total N uptake in the two water treatments (Table 4).

Among the crop establishment methods, DS rice had a lower total N uptake than TP and WS rice in most of the sampling times in both water treatments (Fig. 7). At harvest, the total N uptake of TP rice was higher than that of DS rice ($P < 0.05$ in both water treatments) and WS rice ($P < 0.05$ only in the well-watered treatment, Fig. 7 and Table 4).

Fig. 8 presents the time course of total N uptake as influenced by fertilizer source. In the well-watered treatment, the total N uptakes under the two CRFs were higher than that under PU for most sampling times (Fig. 8a). At harvest, the straw N uptake, grain N uptake and the total N uptake under POC-S120 were significantly higher than those under PU and Polyon 12 (Table 4). In the stress treatment, there was no

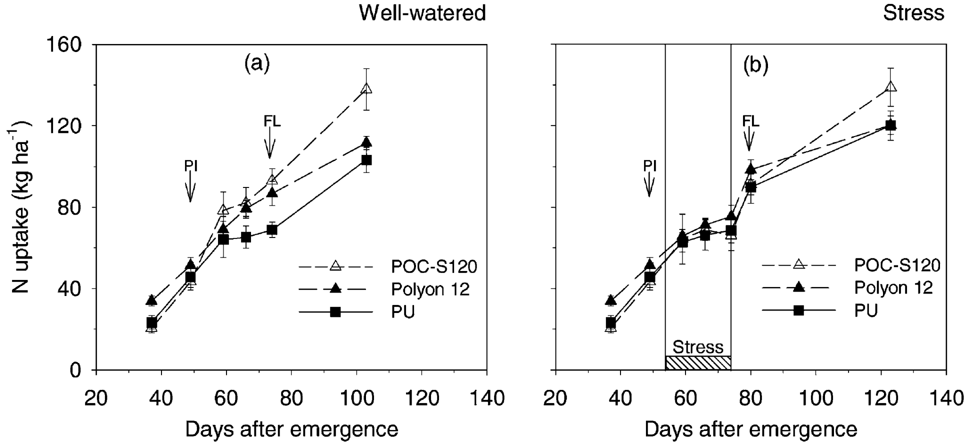

Fig. 8. N uptake of (a) well-watered and (b) stressed rice cv. PSBRc14 as affected by N-fertilizer sources. WS, wet-seeding; DS, dry-seeding; TP, transplanting. The hatched bar indicates the drought stress duration. Vertical bars indicate ±standard errors, $n = 9$. PI, panicle initiation; FL, flowering.

Table 5
Effect of water regime, N-fertilizer source, crop establishment method and their interactions on grain yield, 1000 grain weight and harvest index of rice

Treatment	Grain yield (t ha^{-1})		1000 grain weight (g)		Harvest index	
	Well-watered	Stress	Well-watered	Stress	Well-watered	Stress
Crop establishment (C)[a]						
DS	5.5 b	4.2 a	26.8 a	20.9 a	0.36 a	0.28 a
WS	6.4 a	3.1 b	26.7 a	20.7 a	0.37 a	0.16 a
Transplanting	6.1 a	2.4 c	27.2 a	21.4 a	0.37 a	0.18 b
Fertilizer source (F)[b]						
PU	5.7 a	3.4 a[‡]	26.9 a	21.8 a	0.38 a	0.23 a
Polyon 12	6.3 a	2.8 b	27.0 a	20.1 b	0.37 a	0.18 b
POC-S120	6.0 a	3.5 a	26.9 a	21.1 ab	0.36 a	0.23 a
Mean[c]	6	3.2	26.9	21	0.37	0.21
Water effect	**		**		**	
C and F interaction	NS[d]		NS		NS	
Water, C and F interaction	NS		NS		NS	

[a] Means are average over three fertilizer sources.

[b] Means are average over three crop establishments.

[c] Means are average across all treatments.

[d] Not significant.

** Significant at 1% level.

[‡] In each column/means followed by the same letter are not significantly different at 5% level by DMRT.

significant difference in total N uptake among the fertilizer treatments in most sampling time (Fig. 8b). The grain N uptake under Polyon 12 was, however, significantly less than that under POC-S120 (Table 4).

3.5. Grain yield and grain yield components

In all crop establishment and fertilizer treatments, water stress significantly $(P < 0.01)$ reduced the mean grain yield, 1000 grain weight and harvest index compared with the well-watered treatments (Table 5). Water stress also reduced the mean filled spikelet percentage from 85 to 78% (full data not shown), but the difference in filled spikelet percentage was not significant at the 5% level.

Water by crop establishment interaction had significant effect on yield. Under well-watered conditions, DS rice has a significantly lower yield than TP and WS rice. In the stress treatment, DS rice yielded significantly higher than WS rice and WS rice significantly higher than TP rice. DS rice also had a significantly higher harvest index than WS and TP rice in the stress treatment.

Under well-watered conditions, the two CRFs gave higher yields (though not significant at the 5% level) than PU (Table 5). In the stress treatment, Polyon 12 had significantly lower yield and harvest index than POC-S120 and PU. Polyon 12 also had a lower 1000 grain weight than PU (significant at 5%) and POC-S120 (not significant at 5%).

4. Discussion

4.1. Soil and root characteristics under different crop establishments methods

Changes in the soil moisture characteristic curves brought about by puddling (Fig. 1) affected the duration that available water was accessible for different crop establishment methods. In the 5 cm topsoil, DS rice reached the permanent wilting point later than WS and TP rice (Fig. 2a), indicating that soil water in the topsoil was available for DS rice for a longer period than WS or TP rice. Similarly, at the end of the stress period, available water remained in the 5–10 cm layer for the DS treatment while the TP and WS rice exhausted all available water (soil moisture reached permanent wilting point, Fig. 2b) after 8 days of stress. Our data support findings from Boling et al. (1998) that, after the same stress duration, soil matric potentials in the stressed WS and TP rice were lower (i.e., more difficult for extraction) than those in DS rice. Water stress intensity in DS rice was thus lower than that in WS and TP rice.

Our findings on root distribution (Table 2) supported previous investigators' data (Ingram et al., 1994; Pantuwan et al., 1995; Naklang et al., 1996; Boling et al., 1998) on root differences among TP, WS and DS rice. The differences between WS and TP rice, both grown on puddled soil, may be attributed to plant density (Naklang et al., 1996). The 5–6 plants sampled in the root sampler in WS and DS rice could have produced more roots than the 3 plants per sampler in TP rice. The higher root length density of DS rice than WS rice (both had similar plant density) may be due to soil structure and aeration conditions. The non-puddled soil in DS rice has larger pore sizes and more loose root–soil contact (Pantuwan et al., 1995) than the puddled soil in WS rice. The DS rice soil also had about 2 weeks of flush irrigation after seeding, during which the soil was kept below saturation. This aeration period might have allowed oxygen to penetrate deeper into the soil than with WS and TP rice soils, thus favoring better root development.

Soil penetration resistance increases as the soil dries out (Ringrose-Voase et al., 2000). Our data supported findings of Sharma et al. (1995) that soil penetration resistance of drying puddled soils was higher that that of non-puddled soils. High soil penetration resistance at 10 and 17 cm depths (exceeding 3 MPa, a value believed to be the threshold for root penetration, Whitely et al., 1981) in TP and WS rice may have severely hindered root elongation. Previous studies showed that root length density decreased as soil strength increased (Pantuwan et al., 1995). Higher root length density at deeper soil layers in DS than in WS and TP rice may be attributed to lower soil penetration resistance in the non-puddled soil of DS rice during the stress period. The higher root–shoot ratio of DS rice confirms the relative advantage of DS rice in stimulating root development compared with WS and TP rice, and may affect responses to drought of different crop establishment methods.

4.2. Plant response to drought and rewatering

The experimental results confirmed previous findings that stress at PI delayed anthesis and maturity, reduced growth rate and N uptake during the stress period, and affected the grain yield and harvest index of the rice plant (Castillo et al., 1992; Wopereis et al., 1996b; Yambao and Ingram, 1988). This study gave further insights into the difference in biomass partitioning between the stressed plants after rewatering and the well-watered plants. In the well-watered treatment, biomass continued to increase after anthesis, whereas straw weight remained constant. This was expected because the post-anthesis assimilates in well-watered rice plants should go into the reproductive organs (Kropff et al., 1994). During the recovery stage of the stress treatment, straw weight continued to increase after anthesis of the main culm, indicating that not all assimilates went into the storage organs. We propose the following explanation for the phenomenon. When the plant was subjected to drought during the reproductive phase, floret and spikelet formation were hampered (De Datta, 1981; Yambao and Ingram, 1988; Tuong et al., 2000). When the stress was relieved, storage organs for the assimilates were limited. Because of sink limitation, a part of the carbohydrates assimilated after anthesis went into vegetative organs, resulting in an increase in straw weight. Though this explanation needs validation from a count of spikelet numbers formed before and after stress, it was supported by the observed increase in post-anthesis tiller numbers.

The late-formed tillers continued to stay green at harvest, and were able to retain high N content since the translocation of carbohydrates to the grains was hindered. Higher straw N concentration at harvest (Table 4) and higher straw yield (Fig. 5a, b and Fig. 6a, b) explained the higher straw N uptake in the stressed treatment compared with the well-watered treatment (Table 4).

4.3. Effect of crop establishment on drought stress response

The lower yield of DS rice in the well-watered treatment corresponded well with its lower straw weight and biomass compared with WS and TP rice throughout the crop cycle (Fig. 5). Soil puddling in WS and TP rice reduced the percolation rate (about

9 mm day^{-1}) considerably compared with that in DS rice (about 40 mm day^{-1}). We postulated that the higher percolation rate might cause more leaching, and hence less nutrient availability, which may have affected the growth of DS rice. This was supported by the lower N uptake in DS rice in most of the sampling times (Fig. 7). DS rice also had 2 weeks of flush irrigation during the crop establishment period. Soil moisture below the saturation point might also have reduced the initial growth of DS rice compared with WS and TP rice.

Drought stress reduced the mean yield of DS rice by 21%, WS rice by 51% and TP rice by 60% (Table 4). Boling et al. (1998) also reported that DS rice was less affected by drought than WS and TP rice. We offer the following explanations for the less severe effects of drought on the yield of DS rice in our experiment. As previously discussed, the stressed DS rice could access the available soil moisture in the top 10 cm layer (Fig. 2a and b) for a longer duration during the stress than could WS and TP rice. According to Kamoshita et al. (2000), the water extraction rate in the subsoil is positively correlated with the average root length density at the corresponding depth. Because DS rice had a higher root length density, especially in the soil layers from 5 to 20 cm depths, than WS and TP rice (Table 2), DS rice would be able to extract more water from these layers during the stress period. This was evidenced by lower soil moisture content in the 10–20 cm layer in DS rice compared with WS and TP rice (Fig. 2c). A higher root–shoot ratio at the start of the stress might also have helped DS rice to better overcome the drought stress. Thus, though DS rice was subjected to the same duration of stress, the DS rice plants might be exposed to a lower drought intensity than WS and TP rice. This was supported by the smaller increase in tiller number (Fig. 4b) and straw weight (Fig. 5b) after the stress relief in DS rice compared with that in WS and TP rice, indicating that more carbohydrates could go into the storage organs in DS rice than in WS and TP rice.

Fig. 9 shows the relation between grain yield and total N uptake at the harvest of DS, WS and TP rice in two water treatments. The lines in Fig. 9 indicate the limits of maximum dilution and maximum accumulation of N in rice when grown under well-managed irrigated conditions. The lines were derived by Witt et al. (1999) from 2500 data sets from experiments in Asia with high-yielding cultivars, in which differences in yield were due solely to differences in the availability of nutrient, temperature and radiation. Data points close to or below the maximum accumulation indicate that factors other than the availability of N are limiting rice yield. Most of the experimental data points for the well-watered treatment were within the two lines, and none were close to the maximum dilution, indicating that the rice under study did not suffer from N deficiency. The scatter of points suggests

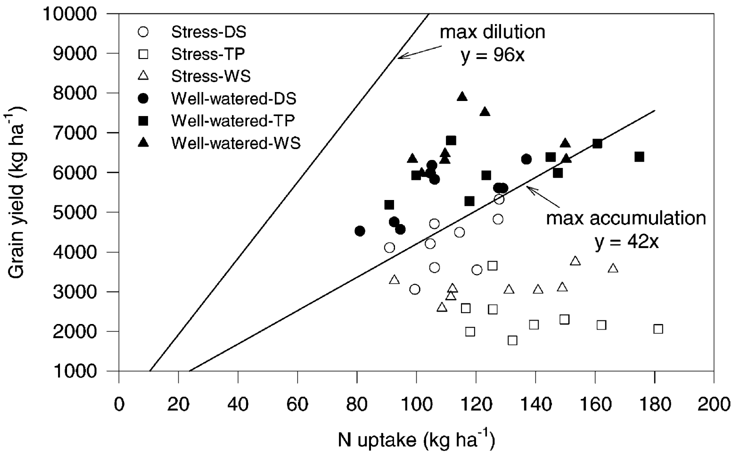

Fig. 9. Relationship between rice grain yield and total N uptake as affected by water regimes and crop establishment methods. WS, wet-seeding; DS, dry-seeding; TP, transplanting. Lines indicate maximum dilution and accumulation of N in the plant for well-managed irrigated rice, adapted from Witt et al. (1999).

that the yield–N uptake relationship was independent of crop establishment method in the well-watered treatment. All points of the three stressed treatments were close to or outside the maximum accumulation line, indicating that moisture stress was indeed limiting yield in our experiment. Data points for DS rice were closer to the maximum accumulation line than those of WS rice, and those of WS rice were closer than those of TP rice. This confirmed that water stress in DS rice was less severe than in WS rice and less severe in WS rice than in TP rice.

4.4. Effect of N-fertilizer source on drought stress response

The well-watered crop was harvested about 105–110 days after seeding. According to the manufacturers, Polyon 12 has a release period of 102 days at constant temperature of 30 °C and vapor-saturated conditions, and POC-S120 120 days at 25 °C and vapor-saturated conditions. Though we did not monitor soil temperature in our experiment, the mean and average maximum soil temperature at 10 cm depth could be estimated at 27.4 and 29.1 °C. This approximation was derived from the relationship between air and soil temperature under rice cultivation based on experimental data at IRRI in 1994 (C. Witt, IRRI, unpublished data). The release periods of POC-S120 and Polyon 12 under the experimental conditions were thus comparable with crop duration under well-watered conditions. Plants in the well-watered treatments probably received adequate nitrogen from the CRFs throughout the crop season, resulting in higher N uptake under CRFs than under PU (Fig. 8a). Higher N uptake under CRFs, however, did not result in significantly higher yield than with PU. The last application of PU (at flowering) increased the N uptake rate of rice during the post-anthesis stage (Fig. 8a), which might help obtain a yield comparable with those under CRFs.

Drought stress delayed the harvest by about 20 days. The prolonged crop duration exceeded the release period of Polyon 12. Most of the urea from Polyon 12 had been released before the stressed plants reached flowering, thus affecting N uptake (Fig. 8b) and biomass accumulation (Fig. 6d) during the post-anthesis stage. In contrast, POC-S120, with its longer release period than Polyon 12, and PU (with the third application at the end of the stress period and the fourth application at flowering, Table 1) were able to supply a higher amount of N to the crop after the stress relief and resulted in significantly higher rice yields than with Polyon 12.

5. Conclusions

Drought stress at PI delayed crop anthesis and maturity and reduced grain yields, but not the total biomass and N uptake of rice cv. PSBRc14. During recovery, the stressed plants formed adventitious tillers and increased straw weight during the post-anthesis stage, at the expense of the translocation of assimilates to the storage organs. Better quantification of the above recovery process will help improve crop growth models, such as ORYZA_W (Wopereis et al., 1996a), in the simulation of yield and biomass partitioning of stressed plants after rewatering.

There was a strong water × crop establishment interaction effect on grain yield. DS rice had a lower yield in the well-watered treatment, but a higher yield in the stress treatment than WS and TP rice. Soil physical properties strongly influenced the effect of water regimes under different crop establishment methods. The unpuddled soil in DS rice may induce more leaching of nutrient in the continuously flooded treatment, but helps DS rice develop a higher and more uniform (with respect to depth) root length density, resulting in increased water availability to the plant during a stress period compared with WS and TP rice. DS rice is more resistant to water stress and may increase the yield stability of rainfed rice more than other crop establishment methods.

Under well-watered conditions, the experimental 4-split PU application performed as well as CRFs in terms of rice yields. In the stress treatment, the drought-induced delay in maturity created a mismatch between the release period of Polyon 12 and crop duration, resulting in a significantly lower yield under Polyon 12 compared with 4-split PU application and POC-S120. The results highlight the importance of anticipating the drought-induced prolongation of crop growth duration in the selection of CRFs so that urea release from CRFs will match crop demand. This difficulty and the high cost of CRFs will prohibit resource-poor farmers in the rainfed environment from using CRFs for the foreseeable future. Multiple-split application of conventional N-fertilizers can do as well as or better than CRFs in both well-watered and stressed conditions and is more likely to be acceptable to farmers.

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