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Performance of rice (*Oryza sativa*) planted on raised-bed under different soil-moisture tensions

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ABSTRACT

An experiment was conducted at New Delhi during rainy season of 2001 and 2002 on aerobic rice (*Oryza sativa* L.) cultivated on raised-beds under different soil-moisture regimes (field capacity, 20 and 40 kPa tensions). The yield was considerably less on raised-beds, varying from 12-24% at field capacity to 40-46% in beds irrigated at 40 kPa soil-water tension compared with the direct-seeded flat land at 20 cm row spacing. Nitrogen in the form of nitrate was dominant in raised-beds (>23%) compared with ammonical form in flat land, and the proportion of nitrate also increased in beds (3-10%) with the increase in soil-moisture stress. Cultivar 'Pusa 44' on raised-beds did not withstand soil-moisture stress, which was reflected in further rapid reduction in its yield by 23-40% when moisture-stress was built-up at 40 kPa tension compared with that at field capacity. The nitrogen content in grain and its uptake also decreased significantly by more than 21 and 42% with the imposition of moisture stress from field capacity to 40 kPa tension. It is necessary to develop special aerobic lowland rice cultivar which can compensate the space left for furrows by producing more number of productive tillers, and can withstand soil-moisture stresses at varying degrees by profuse root growth and proliferation.

Key words : Aerobic rice, Raised-bed, Soil nitrogen, Soil-water tension

Efficient management of irrigation water in rice (*Oryza sativa* L.) cultivation without any reduction in production level is a prime concern. Recently aerobic cultivation of rice on flat unpuddled land or on raised-beds under varying soil-moisture regimes is emerging rapidly. Rice is grown mostly in lowland irrigated puddled ecosystem. This system of growing rice requires huge quantity of irrigation water for land preparation and for maintaining continuous submergence throughout the growth period. This practice has the lowest water productivity, viz. 3,000-5,000 litres for producing 1 kg grain (Bouman, 2001), in comparison with all other cereals. Besides high water requirement, this practice also destroys the soil physical structure, which affects the cultivation of the following wheat crop (Hobbs *et al.,* 2000). As water is becoming scarce all around, direct dry seeding either on flat land or on raised-beds is gaining immense popularity in most of the rice-growing areas of Asia (Borrel *et al.,* 1997; Hobbs and Gupta, 2003). Bed planting of rice is relatively a new concept, where rice crop is grown on the ridges and irrigation is given in the furrows like other upland crops *viz.* wheat, maize etc. Several researchers have pointed out that bed-planting system improves water and nutrient distribution and efficiency, and gives higher yields. Mechanized operations reduce the labour requirements and improve the seeding and weeding practices (Hobbs and Gupta, 2003). There are reports that stress-free bed-planted rice system requires 37-40% less irrigation water than that of puddled transplanted rice, but the yield declines by 5 to 50% or more (Hobbs and Gupta, 2003; Kukal *et al.,* 2005). Most of the current research on bed planting system has been focused on wheat crop and whatever little work has been carried out on rice crop is confined to saving in irrigation water and yield aspects of stress-free beds. However, very little information is available so far regarding the performance of bed-planted, direct-seeded rice when soil-moisture tension or stress conditions at different degrees are imposed. Therefore, the present study was aimed to investigate the crop growth and grain yield of rice crop and the behaviour of nutrient (nitrogen) movement on raised-beds under different soil-water regimes. An attempt was also made to compare the performance of bed-planted rice with that of flat-land system of production.

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MATERIALS AND METHODS

The experiment was conducted during rainy (*kharif*) season in 2001 and 2002 at the research farm of Indian Agricultural Research Institute, New Delhi (altitude 228 m, 28°36 N, 77°12 E). The climate of the area is semi-arid with average annual temperature 25°C and average annual rainfall 650 mm. The experiment in 2002 was conducted at a different location on the farm than in 2001 because of the problem of access to irrigation water experienced in 2001. Soil properties, however, were comparable. Both the soils were classified as Typic Haplustept, with loamy texture, medium in organic C and low in available N (186-215 kg/ha) and medium in P (15-23 kg/ha) and K (339-341 kg/ha) in the surface layer. The soils were neutral in reaction (pH 7.3-8.2) with bulk density 1.53-1.64 Mg/m^3, and had available water content 16-18%. The ground-water table was more than 4 m below the soil surface throughout the crop-growth season at both the sites.

The experiment consisted of four non-puddled treatments. All the treatments were replicated four times in a plot size of 10 m × 7 m in randomized block design. The treatments were: FLDSR: dry-seeded rice on flat land (row spacing 20 cm); $RBDSR_{00}$: dry-seeded rice on raised-beds (bed width 37 cm, furrow width 30 cm and depth 22.5 cm, row spacing on the beds 20 cm, with 47 cm between the paired rows on the beds), irrigated to keep the soil in the furrows at field capacity; $RBDSR_{20}$: same as RB_{00} but irrigated when the soil water tension at 20-cm depth in the centre of the beds reached above 20 kPa (monitored with installed tensiometers); and $RBDSR_{40}$: same as $RBDSR_{00}$ but irrigated when the soil water tension at 20-cm depth in the centre of the beds reached above 40 kPa (monitored with installed tensiometers).

Rice was sown mechanically by a bed planter-cum-seed drill in the raised-bed treatments @ 60 kg/ha in two rows spaced 20 cm apart on the beds, leaving 47 cm space between the rows across the furrows. To compare the performance of rice on raised-beds with that of dry-seeded flat land treatment (FLDSR), rice was sown manually @ of 60 kg/ha in rows regularly spaced 20 cm apart and plots were irrigated as frequently as required to maintain the root zone close to field capacity throughout the growing season. In the raised-bed treatment, irrigation water was applied in the furrows. In all the plots the amount of applied irrigation water was measured with a flow meter installed in flexible hoses.

Application of 13.1 kg P and 50 kg K/ha was made to all the treatments uniformly. Nitrogen was applied @ 120 kg/ha in three split applications, viz. 50% basal, 25% at tillering and 25% at flowering. Micronutrients, Zn ($ZnSO_4$) and Fe ($FeSO_4$) were applied basal @ 25 and 50 kg/ha, respectively. Composite soil samples were collected at the beginning of the experiment from both the sites. The samples were air-dried, ground to pass through 2 mm sieve for determining various physico-chemical characteristics and 0.5 mm sieve for determination of organic carbon. Rice variety 'Pusa 44' was used for the experiment.

From all the plots 2 row sections of 50 cm each were sampled at different stages of growth, viz. maximum tillering, panicle initiation , flowering and physiological maturity. Of these samples, the dry weight of leaves, stems and panicles was determined after oven drying for 3-5 days at 60°C until a constant weight was reached. The height of main tillers in 2 rows of each plot was measured before harvest. Tillers were counted at the time of harvesting from 1 m^2 area with the help of 1 m x 1 m quadrant. Grain yield of each plot was recorded from 6 m^2 area at 14% moisture content and then converted on hectare basis. Water-use efficiency was calculated as weight of grains over cumulative amount of irrigation water inputs used during the crop-growth period.

RESULTS AND DISCUSSION

Biomass accumulation

The change in row spacing from 20 cm (FLDSR) to that on raised-beds ($RBDSR_{00}$) significantly decreased the biomass production throughout the growth period (Table 1). Nearly 35% area was left unsown in $RBDSR_{00}$, which caused decline in biomass production at panicle initiation (PI) and flowering stages by 15 and 30% in 2001, and 30 and 15% in 2002, respectively, compared with closed-space treatments (FLDSR). The corresponding decrease at grain filling and harvest was more than 15% during both the years. When the beds were subjected to soil-moisture stress of 20 and 40 kPa tension ($RBDSR_{20}$ and $RBDSR_{40}$), biomass production further declined considerably and the effect was more pronounced from PI to harvest. At PI stage of growth, biomass production in $RBDSR_{20}$ and $RBDSR_{40}$ treatments declined further by 15 and 30% in 2001, and 12 and 16% in 2002, respectively, compared with beds irrigated at stress-free condition ($RBDSR_{00}$). This decline in biomass production in the former can be attributed to less plant population per unit area, which also reflected in lower LAI, panicles/m^2 and other growth-attributing parameters. It was also due to the deleterious effect of soil-moisture stress on growth contributing characters, viz. inhibition of cell division and cell enlargement, optimum leaf production, decline in leaf area and enhanced leaf senescence, leading to reduced canopy photosynthesis as well as reduction in plant height, tillering density and other associated parameters (Yoshida, 1981; Nieuwenhuis *et al.*, 2002). 'Pusa 44' used in the experiment is a traditional lowland rice cultivar. Therefore, under aerobic conditions it could not perform well in bed as well as flat-planted system, and when moisture stress was imposed, its performance declined further. However, in all the treatments, biomass accumulation increased with advancement in the stage of growth. The rate of increase was very rapid from PI stage to flowering stage, but thereafter up to harvest it increased at a slower rate.

Growth and yield attributes

The effect of establishment technique was negligible on plant height, as was evident from the non-significant change observed in bed-planted rice ($RBDSR_{00}$) compared with flat-land rice (FLDSR) at similar moisture regime (Table 1). However, the effect of soil-moisture stress in decreasing the plant height in bed-planted rice irrigated at 20 and 40 kPa tensions ($RBDSR_{20}$ and $RBDSR_{40}$) was quite visible, especially in $RBDSR_{40}$, where the plant height decreased by 11-14% compared with the stress-free treatment on beds ($RBDSR_{00}$) in both 2001 and 2002.

Panicles/m^2 were significantly affected by the method of establishment as well as the moisture stress imposed on beds. Changing the row spacing from 20 cm (FLDSR) to 20-47-20 cm in bed-planted ($RBDSR_{00}$) rice significantly reduced the number of panicles/m^2. When beds were irrigated at 20 ($RBDSR_{20}$) and 40 kPa ($RBDSR_{40}$) tensions, the number of panicles/m^2 declined further by more than 7 and 13% in 2001 and 2002, respectively. It could be attributed to stress at tillering, which reduced the number of tillers and panicles/hill and also increased the mortality of productive tillers (Lu *et al.*, 2002).

Though the number of spikelets/panicle was unaffected by the method of establishment, evident from a similar number under bed ($RBDSR_{00}$) and flat land (FLDSR), the moisture stress on bed-planted rice significantly decreased the production of spikelets/panicle. Compared with $RBDSR_{00}$, the number of spikelets production/panicle declined under $RBDSR_{20}$ and $RBDSR_{40}$ by 9 and 16% in 2001, and 8 and 13% in 2002, respectively. Several workers also endorsed similar views that if moisture stress prevails between panicle initiation and flowering, there will be a sharp decline in spikelets/panicle and thus the number of grains/panicle (Nieuwenhuis *et al.*, 2002).

The effect of moisture stress on bed-planted rice showed a linear relationship of decreasing trend in spikelet fertility with the increase in magnitude of moisture stress. Compared with $RBDSR_{00}$, it decreased in $RBDSR_{20}$ by 3-11% and again in $RBDSR_{40}$ further by 7-11%, during both the years. However, bed-planted rice ($RBDSR_{00}$) with moisture regime similar to that of FLDSR did not show any decline in fertility percentage of spikelets. Thus it shows that soil-moisture stress had significant impact on decreasing the fertility percentage of spikelets rather than the method of establishment techniques. Nieuwenhuis *et*

Table 1. Biomass accumulation, and growth and yield parameters of rice under different methods of establishment

Treatment	Biomass accumulation (g/m^2)				Plant height (cm)	Panicles/m^2	Spikelets/ panicle	Fertile spikelets (%)	Harvest index	1,000-grain weight (g)	Grain yield (t/ha)	WUE (kg/ha-mm)
	Panicle initiation	Flowering	Grain filling	Harvest								
2001												
FLDSR	465	1,210	1,406	1,502	74.0	296	120	74.2	0.28	20.31	4.20	6.13
$RBDSR_{00}$	392	820	1,122	1,223	72.8	220	123	71.1	0.27	20.45	3.21	5.66
$RBDSR_{20}$	335	696	997	1,090	69.4	205	112	68.9	0.29	19.51	3.11	6.25
$RBDSR_{40}$	252	578	768	930	62.4	191	103	62.8	0.26	18.65	2.50	5.96
SEm ±	3	5	5	6	0.6	3	1	0.7	0.02	0.12	0.03	0.02
CD (P=0.05)	9	16	17	20	1.8	8	4	2.4	NS	0.38	0.09	0.05
2002												
FLDSR	477	1,134	1302	1,397	67.3	288.2	122	72.0	0.29	19.04	4.21	5.17
$RBDSR_{00}$	334	964	1060	1,185	71.2	234.6	121	73.9	0.31	20.10	3.72	5.11
$RBDSR_{20}$	292	886	946	1,084	69.6	220.6	111	65.7	0.28	19.43	3.01	4.65
$RBDSR_{40}$	290	809	927	1,032	63.4	199.3	105	60.9	0.22	18.36	2.27	3.91
SEm ±	2	9	7	4	1.2	199	1	1.3	0.02	0.13	0.04	0.02
CD (P=0.05)	7	30	21	12	3.9	4	4	4.0	0.05	0.42	0.12	0.05

al. (2002) had opined that if moisture stress persisted at flowering or early physiological maturity stages, it increased the sterility of spikelets, resulting in a sharp reduction in percentage of fertile spikelets, number of grains/panicle and even 1,000-grain weight.

Harvest index did not vary significantly, irrespective of the establishment method. In the bed treatments, HI did not decline when the soil-water tension increased from field capacity ($RBDSR_{00}$) to 20 kPa tension ($RBDSR_{20}$). Only when the soil was allowed to dry out to 40 kPa suction ($RBDSR_{40}$), it decreased by more than 25% compared with $RBDSR_{00}$ in 2002 (Table 1).

Although it is generally believed that 1,000-grain weight is the most stable varietal character because grain size is rigidly controlled by the size of the hull (Yoshida, 1981), in the present investigation different soil-moisture regimes had significant impact on this relatively stable yield-controlling parameter. Raised-beds irrigated at 40 kPa tension ($RBDSR_{40}$) showed a reduction of 8.3% compared with stress-free treatment on beds (RB_{00}). Nieuwenhuis *et al.* (2002) asserted similar views of reduction In 1,000-grain weight under moisture stress.

Grain yield

The establishment technique affected the grain yield significantly (Table 1). It was the highest in flat land (FLDSR) with 20 cm row spacing. A change in the row spacing in dry-seeded rice from 20 cm (FLDSR) to 20-47-20 cm raised-beds at similar water regime ($RBDSR_{00}$) decreased the yield by 12 and 24% during 2001 and 2002 respectively. In the bed treatments, grain yield further declined significantly in the treatments with increased soil-moisture stress from near continuous saturation ($RBDSR_{00}$) to 20 kPa ($RBDSR_{20}$) and 40 kPa ($RBDSR_{40}$) tensions. The corresponding reduction of grain yield in $RBDSR_{20}$ and $RBDSR_{40}$ in comparison with $RBDSR_{00}$ was 4-19 and 23-40%, respectively during 2001 and 2002. The $RBDSR_{40}$ treatment recorded the lowest grain yield of 2.27 t/ha in 2001 and 2.50 t/ha in 2002.

This decline in yield under bed-planted rice was caused apparently by wider spacing, which was not compensated by more number of tillers or panicles (Borell *et al.*, 1997). The effect of wider spacing was also reflected by lower leaf-area index (LAI) and biomass production throughout the growth period. Imposition of soil-water tension on $RBDSR_{20}$ and $RBDSR_{40}$ treatments certainly ran the risk of yield reduction because of possible effect on the yield-attributing characters of the crop (Lu *et al.*, 2000; Nieuwenhuis *et al.*, 2002). It appears that the cultivar was unable to compensate the yield reduction in the raised-beds planting treatment under wider spacing (RBDSRs). Moreover, 'Pusa 44' might not be suited for aerobic conditions, leading to rapid decline in its yield with increase in soil-water tension.

Differences in water-use efficiency (WUE) with respect to irrigation water use among the treatments were relatively minor in absolute terms except in raised-beds irrigated at 40 kPa tension (RB_{40}), which recorded the lowest WUE during both the years (Table 1). There was a decline in WUE by 4 and 24% in RB_{40} compared with the treatment with highest WUE (RB_{20}) during 2001 and 2002, respectively. The lower WUE in RB40 was mainly due to significant reduction in grain yield (22-38%) compared with that in stress-free bed treatment (RB_{00})

Nitrogen content and uptake

The grain N content in the grain was significantly higher (13-21%) in bed-planted rice ($RBDSR_{00}$) compared with that in flat land (FLDSR) with similar stress-free soil-moisture regime (Table 2). However, with the imposition of moisture stress, there was a significant reduction in grain N content by more than 8 and 21% in the beds irrigated at 20 ($RBDSR_{20}$) and 40 kPa ($RBDSR_{40}$) tensions compared with stress-free beds ($RBDSR_{00}$) during both the years. The higher grain N content in the bed-planted rice (RB_{00}) compared with that on flat land (FLDSR) was due to the application of nitrogen between the ridges on the beds. Straw N content however, did not show any significant variation among the treatments except $RBDSR_{40}$, where moisture stress decreased the N uptake in the grain and thus remained significantly higher in the straw. The range of values obtained for grain N content in the present investigation closely matched the values as reported by Marr *et al.* (1999).

Table 2. Grain and straw nitrogen content and uptake of rice at harvest

Treatment#	Grain N (%)	Straw N (%)	Grain N uptake (kg/ha)	Straw N uptake (kg/ha)	Total N uptake (kg/ha)
2001					
FLDSR	1.33	0.54	55.90	58.64	114.55
$RBDSR_{00}$	1.51	0.51	48.53	45.53	94.06
$RBDSR_{20}$	1.36	0.54	42.31	42.24	84.55
$RBDSR_{40}$	1.12	0.51	28.10	34.75	62.85
SEm±	0.02	0.01	0.37	0.30	0.25
CD (P=0.05)	0.05	NS	1.18	0.95	0.85
2002					
FLDSR	1.28	0.51	53.60	50.07	103.67
$RBDSR_{00}$	1.54	0.54	57.33	43.82	101.15
$RBDSR_{20}$	1.42	0.58	42.82	45.72	88.54
$RBDSR_{40}$	1.22	0.47	27.64	37.78	65.41
SEm±	0.02	0.02	0.32	0.50	0.41
CD (P=0.05)	0.05	0.05	1.04	1.27	1.31

Total N uptake by grain at harvest was significantly less (13%) in bed-planted ($RBDSR_{00}$) compared with flat-land (FLDSR) rice during 2001, but in 2002 both FLDSR and $RBDSR_{00}$ had similar uptake (Table 2). The raised-beds irrigated at 20 kPa tension ($RBDSR_{20}$) had a significant lower grain N uptake by 13% in 2001 and 25% in 2002 compared with stress-free beds ($RBDSR_{00}$). There was a further reduction (> 26%) when the beds were irrigated at 40 kPa tension ($RBDSR_{40}$). Total straw-N uptake also reflected a similar pattern of reduction in N uptake in wider space beds (RBDSRs) compared with close-space flat land (FLDSR) and a continuous decline in beds with increase in soil-moisture tension ($RBDSR_{20}$ and $RBDSR_{40}$).

The pattern of total N uptake by grain and straw revealed a close relationship with the total biomass accumulation at harvest. Reduction in plant population per unit area and imposition of moisture stress further in raised-beds ($RBDSR_{20}$ and $RBDSR_{40}$) reduced the root weight density as well as number of productive tillers in beds, and thereby reduced the total N uptake by grain and straw compared with that in N stress-free flat bed (FLDSR) (Padhi, 1999).

Soil N content

Profile distribution of soil NH_4^+-N content up to a depth of 90 cm was studied at maximum tillering and flowering stages of rice growth (Fig. 1). At tillering stage, raised-beds ($RBDSR_{00}$) had 10 %less NH_4^+-N content in the surface layer (0-15 cm) than in flat lands with similar moisture regimes (FLDSR); the differences in reduction were significant throughout the depth of the profile. Again, on imposition of soil-moisture stress, $RBDSR_{20}$ and $RBDSR_{40}$ treatments showed a further decline in the NH_4^+-N content, particularly in the surface (0-15 cm) and immediate subsurface layers (30-45 cm). In both the seasons, in $RBDSR_{40}$ treatment the soil NH_4^+-N content declined by more than 20 %in the surface layer (0-15 cm) compared to $RBDSR_{00}$ (at 0-15 cm, $RBDSR_{00}$: 73.6, $RBDSR_{20}$: 68.1 and $RBDSR_{40}$: 58.1 kg/ha). With increase in the period of dryness, a decreasing trend of total profile NH_4^+-N content was observed among the treatments. However, irrespective of the treatment, soil NH_4^+-N content gradually decreased along with increase in depth.

As at tillering stage, at flowering also a similar trend of NH_4^+-N was observed among the treatments i.e. FLDSR recorded the highest, followed by $RBDSR_{00}$, $RBDSR_{20}$ and $RBDSR_{40}$, respectively (Fig. 1). However, the amount of NH_4^+-N content was lower than at tillering stage of growth irrespective of the treatment. However, the NH_4^+-N content at flowering stage was higher than that of PI

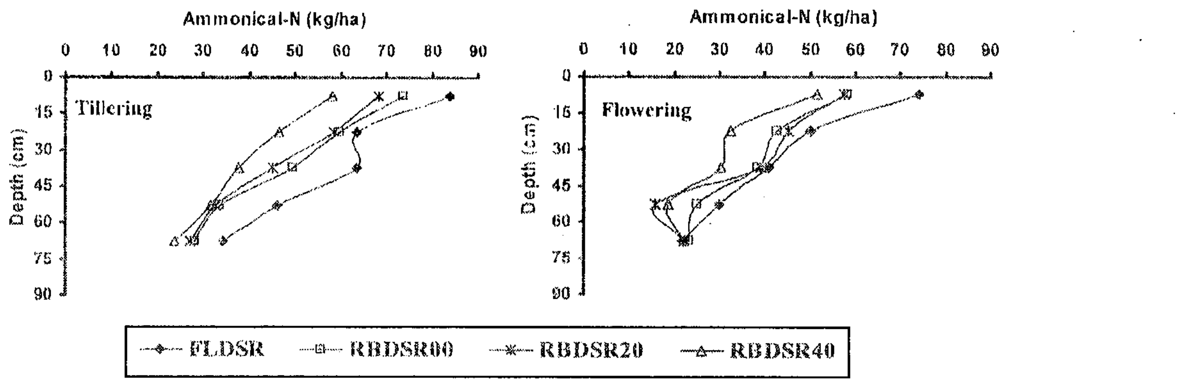

Fig. 1. Ammonical nitrogen content under different treatments at tillering and flowering stages of rice

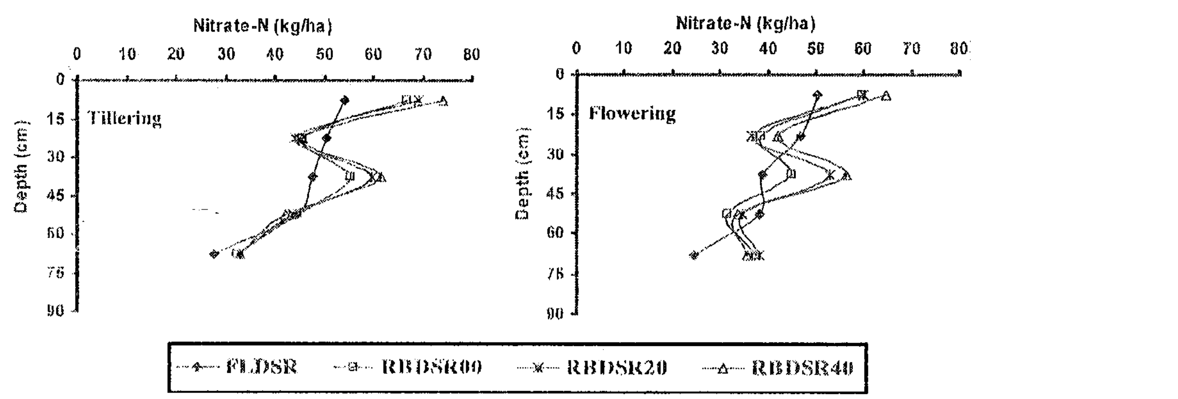

Fig. 2. Nitrate-nitrogen content under different treatments at tillering and flowering stages of rice

stage in 2001 due to the application of urea just 10 days before heading. The reduction of NH_4^+-N content at later stages of growth was due to rapid uptake by the crop. Tripathi *et al.* (1997) had also reported low soil NH_4^+-N content during the dry season in lowland rice. This is because of the presence of wetter water regimes, which favour retention of NH_4^+-N content, thus retarding its conversion into nitrate form. Similar findings of continuous decline in soil NH_4^+-N content from early stages of crop growth to later stages were also reported by Das *et al.* (1998). Lower NH_4^+-N content under aerobic treatments were due to rapid oxidation of NH_4^+-N to NO_3^--N (Aulakh and Singh, 1997).The degree of reduction in NH_4^+-N under $RBDSR_{20}$ and $RBDSR_{40}$ treatments showed a close association with the period of exposure to the aerobic conditions, being lowest in the $RBDSR_{40}$. There was a decrease in NH_4^+-N content with the increase in degree and duration of dryness, as evident from the $RBDSR_{40}$ treatment.

Contrary to the NH_4^+-N content of the soil, the distribution of NO_3^--content in its profile reflected a reverse trend. Compared with FLDSR, the $RBDSR_{00}$ treatment had significantly higher NO_3^--N content (> 23%) in the surface (0-15 cm) layer. The NO_3^--N content increased further in $RBDSR_{20}$ and $RBDSR_{40}$ treatments by more than 3 and 10% respectively compared with RB_{00}. The prolonged aerobic conditions that persist under raised-beds (especially in $RBDSR_{20}$ and $RBDSR_{40}$) promoted rapid oxidation of the applied inorganic N, which in turn accelerated the nitrification process, thereby resulting in accumulation of NO_3^--N in the soil.

Depth-wise distribution of NO_3^--N content showed a gradual decreasing pattern up to a depth of 30 cm among the treatments, beyond which no regular pattern was observed in raised-beds, but a continuous decrease was observed in flat lands (FLDSR) (Fig. 2). However, in both raised-beds and flat lands, the surface layer (0-15 cm) had the highest accumulation of NO_3^--N form, primarily due to the prevalent aerobic environment. Katyal *et al.* (1987) also reported higher NO_3^--N content (up to 70% of applied N) at surface layers (0-30 cm). Raised-bed treatments had also significantly higher total profile NO_3^--N content (up to a depth of 90 cm) compared with FLDSR treatment, which decreased gradually with advancement in the stage of growth. This could be attributed to rapid uptake by the crop at later stages of growth. Application of fertilizer in the form of urea at early stages of growth along with slow uptake rate favoured greater accumulation of NO_3^--N in the soil compared with that at later stages of growth.

It was concluded that bed-planted rice with wider spacing reflected a significant decline in grain yield production compared with normally spaced aerobic flat-land rice. The cultivar 'Pusa 44' was unable to compensate for loss in yield in beds for the reduced area due to furrows as well as moisture stresses.

REFERENCES

Aulakh, M.S. and Singh, B. 1997. Nitrogen losses and N-use efficiency in porous soils. *Nutrient Cycling and Ecosystems* **47**: 197–212.

Borrell, A., Garside, A. and Fukai, S. 1997. Improving efficiency of water for irrigated rice in a semi-arid tropical environment. *Field Crop Research* **52**: 231–248.

Bouman, B.A.M. 2001. Coping with the water crisis: water management strategies in rice production. Paper presented at *International Symposium on Sustainable Soil and Water Resources Management*, held during 30-31 May 2001, at Diliman Quezon city, Philippines.

Das, R., Das, D.K. and Das, B. 1998. Transformation of N in submerged soils in relation to yield and nutrition of rice as affected by sources and methods of N application. *Oryza* **35**(4): 338–342.

Hobbs, P.R., Singh, Y., Giri, G.S., Lauren, J.G. and Dusbury, J.M. 2000. Direct seeding and management of water as a scarce resource: issues and options in rice culture. *Sustainability of Rice in the Global Food System*, pp. 175–192.

Katyal, J.C., Singh, B., Vlek, P.L.G. and Buresh, R.J. 1987. Efficient nitrogen use as affected by urea application and irrigation sequence. *Soil Science Society of America Journal* **51**: 366–370.

Kukal, S.S., Humphreys, E., Yadvinder Singh, Timsina, J. and Thaman, S. 2005. Performance of raised-beds in rice-wheat systems of northwestern India. In: Roth, C., Fischer, A.R., Meisner, C. (Eds), Evaluation and performance of permanent raised-bed cropping systems in Asia, Australia and Mexico. *Proceeding of an International Workshop,* ACIAR Proceedings, vol. 21. *Griffith, NSW,* held during 1-3 March ACIAR, Canberra, Australia, pp. 26–40.

Lu, J., Ookawa, T. and Hirasawa, T. 2002. The effects of irrigation regimes on the use, dry matter production and physiological responses of paddy rice. *Plant and Soil* **223**: 207–216.

Marr, K.M., Batten, G.D. and Lewin, L.G. 1999. The effect of nitrogen fertilizer on yield, nitrogen and mineral elements in Australian brown rice. *Australian Journal of Experimental Agriculture* **39**(7): 873–880.

Nieuwenhuis, J., Bouman, B.A.M. and Castaneda, A. 2002. Crop-water responses of aerobically grown rice: preliminary results of plot experiments In: Bouman, B.A. M. Hengsdijk, H. Hardy, B. Bindraban, P.S. Tuong, T.P. and Ladha, J.K. (Eds) *Water-wise Rice Production*, pp. 177-185. IRRI, Los Baños, Philippines.

Page, A.L. 1991. Methods of Soil Analysis. 2nd edn. American Society of and Soil Science, Madison, Wisconsin, USA.

Padhi, A.K. 1999. Production potential, energetics and economics of different systems of planting rice. *Oryza* **36**: 234–237.

Tripathi, B.P., Ladha, J.K., Timsina, J. and Pascua, S.R. 1997. Nitrogen dynamics and balance in intensified rainfed lowland rice-based cropping systems. *Soil Science Society of America Journal* **61**: 812–821.

Yoshida, S. 1981. *Fundamentals of Rice Crop Science*, 269 pp. International Rice Research Institute, Los Banos, Philippines.