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ARTICLE

Uptake efficiency of ^{15}N-urea in flooded and aerobic rice fields under semi-arid conditions

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Abstract The sustainability of traditional rice (Oryza sativa L.) cultivation in many Asian countries is being questioned due to severe water shortage conditions, envisaging the need for development of water-saving rice production technologies. A 2-year-field study on a typic Haplustalf soil was conducted to compare traditional transplanted rice–maize system with water-saving aerobic rice–maize system, with an overall objective of investigating the fate of fertilizer nitrogen (N) using ^{15}N-labeled urea. Results from the field experiments showed that the rice plants positively responded to N fertilizer application. The average fertilizer N recovery by rice crop over the 2 years in aerobic rice was 26 kg per 100 kg of applied fertilizer N in the main field and 21 kg per 100 kg of applied N in the microplot, while the recoveries were 41 and 32 kg ha^{-1} per 100 kg of applied N in traditionally cultivated rice under flooded conditions. The fraction of ^{15}N that was found in soil after the harvest of rice crop ranged from 11.4 to 47.1 kg ha^{-1} in aerobic rice and 14.2–51.4 kg ha^{-1} in flooded rice. Average recovery of ^{15}N fertilizer in maize after the first growing season was 3.3 %, and the corresponding recovery in soil was 19 %. An additional 1.3 % of the fertilizer was recovered by crops during the two subsequent seasons. This study indicates the need to develop management practices that improve N use efficiency in aerobic rice by reducing losses to improve yields and reduce N export to the environment.

Keywords Aerobic rice · ^{15}N-labeled nitrogen · Nitrogen use efficiency · Residual N

Introduction

In Asia, the traditional rice transplanting method of cultivation faces severe yield limitations due to frequent monsoon rain failure which results in water stress during critical periods of rice growth. The agricultural sector in Asia withdraws 90 % of developed freshwater resources; of this more than 50 % is used to irrigate rice (Barker et al. 1998; Maclean et al. 2002; Molden et al. 2007). It was estimated that by 2025 about 15–20 million ha of irrigated rice cultivation might be negatively affected by water scarcity (Tuong and Bouman 2003). The increasing demand for water mainly from municipal and industrial sectors threatens the sustainability of irrigated rice production and calls for development of novel technologies that can reduce water requirement and maintain yields. The aerobic rice production system is considered one such water-saving rice technology (Bouman et al. 2005; Kadiyala et al. 2012), and consists of rice cultivation under non-puddled, non-saturated soil conditions. This concept is mainly targeted for irrigated lowlands, where water is not sufficient for rice cultivation and suitable uplands and

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where facilities for supplemental irrigation are available (Belder et al. 2005).

Limited information is available on the effects of nutrient supply on plant growth and grain yield of aerobic rice (Nie et al. 2008). The changes in water use associated with the aerobic system may result in altered soil N transformations and plant N uptake patterns. The unique water management system followed in aerobic rice with several dry-wet cycles may result in remarkable changes in biological, chemical, and physical properties of the soil, and consequently, influence the transformation and migration of N fertilizer in soil. In aerobic system, N losses associate with NO_3^- form will likely increase, and losses associated with NH_4^+ like ammonia volatilization may decrease as compared to flooded rice grown in anaerobic soil conditions (Belder et al. 2005; Zhang et al. 2009). Research has indicated that in rice a mixture of NO_3^- and NH_4^+ forms of N results in greater N uptake and grain yield of compared to providing all of one form or the other (Ta et al. 1981; Qian et al. 2004). Therefore, rice production systems that employ water-saving techniques may result in greater N uptake but also may result in higher N loss and reduced growth if NO_3^- availability and plant growth do not coincide.

Nitrogen transformations in lowland soils have been studied extensively (Reddy and Patrick 1976; De Datta and Buresh 1989; Buresh and De Datta 1991; George et al. 1992; Kundu and Ladha 1995). Current N fertilizer recommendations for rice in general have, therefore, been established for rice production under continuously submerged conditions. Since the aerobic rice production system is a recent development, relatively few studies have been conducted on N dynamics and N fertilizer use efficiencies. Generating information on N dynamics and fertilizer nitrogen use efficiency (FUE) for rice growing regions of the world may be critical as the aerobic rice production method of rice is increasingly adopted as a technique to conserve water. There is also the need to critically review the benefits and drawbacks of growing rice using water-saving aerobic rice production practices, its impact on the environment and on the sustainability of rice cultivation.

Due to lack of water, the traditional continuous rice production systems where rice is grown in a 2–5 cm deep flood water throughout the season have shifted to rice–maize (Zea mays L.) (R-M) systems. Furthermore, the rice establishment method itself is shifting from a flooded to aerobic system, where rice crop is grown under non-flooded, unpuddled soil by supplementary irrigation and external inputs. The R-M system is gaining popularity in many Asian countries due to rapidly increasing livestock and human populations. Studies on N dynamics and balances in R-M cropping system are limited. Additional research is required to understand the various nutritional aspects of R-M systems that will improve productivity, profitability, and sustainability of both crops. The ^{15}N-labeled fertilizers can effectively be utilized to study the flow and fate of N between crops in crop sequence studies, as it allows accurate quantification of applied N in various sinks such as crops, available soil N and soil organic matter N pools (Shinde et al. 1985; Timmons and Cruse 1991; Powlson and Barraclough 1993; Singh et al. 2001). Information on long-term N retention patterns in nutrient intensive R-M cropping systems, especially under different rice establishment methods, is essential to evaluate the effect on FUE of the entire cropping system. To address some of these research questions, a field experiment was conducted with ^{15}N-labeled fertilizer in aerobic and flooded R-M cropping system to (i) study the effect of N rates on N uptake, grain yields, and FUE of aerobic rice in comparison to flooded rice, (ii) determine the total recovery efficiency of applied inorganic N in the crop and soil in R-M rotation, and (iii) study the uptake of residual ^{15}N by crops during the subsequent three seasons.

Materials and methods

Study area

A field experiment was conducted over two consecutive years (2009–10 and 2010–11) in a rice–maize cropping sequence at the Acharya NG Ranga Agricultural University Research farm, Hyderabad, India. The soil at the experimental site was a typic Haplustalf with a pH of 8.0, organic C of 0.51 %, Olsen's extractable P of 0.012 g kg^{-1}, and ammonium acetate extractable K of 0.122 g kg^{-1} in the surface 15 cm soil (Table 1).

Experimental details

The experiment was laid out in a split plot design with rice crop establishment methods as main plots and N levels as sub plots with three replications. Rice–maize was the normal cropping system followed at the experimental site before the current experiment was initiated. The experiment was described in detail by Kadiyala et al. (2012). The research area used for aerobic rice production was dry plowed, harrowed, and leveled; the seeds were planted by hand with the MTU-1010 variety, in rows spaced 22.5 cm apart at a seeding rate of 300 seeds m^{-2}. Planting was followed by pre-emergence herbicide application of pendimethalin at 1.0 kg active ingredient ha^{-1}. Manual hand weeding was done at 30 and 45 days after planting (DAP). Aerobic plots were flood irrigated with 5 cm water when the soil moisture tension at the surface 15 cm depth

Table 1 Physical and chemical soil properties of the surface (0–30 cm) profile at the experimental site measured during 2009

Soil parameter	0–15 cm	15–30 cm	Method of analysis
Sand (%)	53.6	53.6	International pipette method Piper (1966)
Silt (%)	13.0	11.0	
Clay (%)	33.4	35.4	
pH (2.5:1 in water)	8.0	8.2	Beckman pH meter with glass electrode Jackson (1967)
Organic C (%)	0.51	0.48	Wet digestion method Walkley and Black (1934)
KM_nO_4 extractable N (g kg^{-1})	0.099	0.088	Alkaline potassium permanganate method Subbiah and Asija (1956)
Olsen's extractable P (g kg^{-1})	0.012	0.007	U.V, Visible spectrophotometer Olsen et al. (1954)
Ammonium acetate extractable K (g kg^{-1})	0.122	0.078	1 N Neutral ammonium acetate using flame photometer Muhr et al. (1965)

reached −30 kPa during the crop period measured using Delta-T Devices theta probe with a ML2 sensor capacitance probe. There was no ponded water except for parts of the days when irrigation occurred or when large amounts of rain were received.

Flooded rice plots were puddled using a tractor-drawn cage wheel and kept continuously flooded from transplanting until 1 week before harvest. Transplanting using 30 days old seedlings, raised separately in the nursery, was done at 20 × 15 cm spacing. Water depth was initially maintained at 2 cm and gradually increased to 5 cm from panicle initiation to 10 days before maturity. Mid-season drainage, which involves removal of surface water from the field at maximum tillering period, was done to check the unproductive tillers. Manual hand weeding was done at 20 and 30 days after transplanting (DAT) in flooded rice. Transplanting in flooded plots (nursery) as well as aerobic plots was done on the same day. The total water input (irrigation + rainfall) to aerobic rice in both the years ranged from 645 to 967 mm compared to 1,180–1,546 mm in flooded rice. Sufficient bund height was maintained to arrest runoff losses form the experimental plots. Four N treatments were selected for the study: (i) No N-Control (0 kg N ha^{-1}), (ii) 60 kg N ha^{-1}, (iii) 120 kg N ha^{-1}, and (iv) 180 kg N ha^{-1}.

Microplots were created by inserting leak-proof, galvanized iron frames (2.0 m long × 2.0 m wide × 0.6 m high) with top and bottom open, to a 30 cm depth in aerobic and flooded treatment plots. The reasons for using these microplots were to control lateral movement of water, to facilitate measurement of vertical flow, and to confine ^{15}N fertilizer to the microplot. The fertilizer N was applied as per the treatments imposed in the form of urea in three equal splits: the first one as basal and the other two, at active tillering and at panicle initiation stages. The required quantity of urea according to the treatments was applied to the entire plot except the microplots and uniformly incorporated in the soil. The microplots were covered with polythene sheets at the time of urea application on main plots so that the fertilizer urea would not spill into the microplots. The microplots were then fertilized with ^{15}N-labeled urea having 5 atom % excess ^{15}N according to the treatments in three split doses. In aerobic rice treatment plots, the N fertilizer was applied by side-dressing in each plant row in three splits over time. The fertilizer application was followed by irrigation. In the flooded rice system, the N fertilizer was broadcasted in puddled soil and incorporated and the fields were flooded the day after fertilizer application. Microplots were maintained with the same water regime as the main plots, but received irrigation water separately using a pipe to avoid exchange of N. The whole plot including the microplot received a uniform rate of 26 kg ha^{-1} P as single superphosphate and 33 kg ha^{-1} K as muriate of potash at the time of planting in aerobic method and at final puddling in flooded treatment. All the required plant protection measures were adopted during the crop growth as per the standard procedures (Raju SCh and Reddy 2013).

At physiological maturity, yield components such as the number of panicles m^{-2}, number of spikelets $panicle^{-1}$, 1,000 grain weight, and final yields were determined. Grain and straw samples from 49 m^2 in each plot and the entire microplot were collected, plants were hand threshed to separate into grain and straw, and each component was dried and weighted to determine grain and straw yield. Aerobic rice plots were harvested during 1st week of November and flooded rice plots a week later (2nd week of November) due to delay in maturity. The N concentration in grain and straw was determined using micro kjeldahl digestion, distillation, and titration (Bremner and Mulvaney 1982) to calculate the above ground N uptake. Grain and straw grown in all microplots were ground in a ball mill to pass through 1 mm sieve and were analyzed for atom percent excess N using mass spectrophotometer (Delta V plus, Thermo Fisher Scientific, Bremen, Germany). Weed samples were collected at the time of two-hand weedings in both aerobic and flooded microplots plots, dried and ground in a ball mill to pass through 1 mm sieve, and were analyzed for atom percent excess N. Immediately after the rice plants were harvested, soil samples were collected in all microplots from four spots at 15 and 30 cm depth using a 2-cm-diameter hand-operated core sampler, and were air dried and ground to pass 2 mm sieve, and were analyzed for ^{15}N. Total-N and atom percent ^{15}N were analyzed using an Isotope ratio mass spectrometer at the University of Agricultural Sciences, Bengaluru, India.

After rice harvest, the plots were kept fallow for 15 days and maize (DeKalb 800 m hybrid) was hand dribbled in the succeeding season under no tillage conditions with a spacing of 60 × 20 cm in both main and microplots. The maize crop received 120 kg N, 26 kg P, and 33 kg K ha^{-1}. Both P and K fertilizers were applied as basal, while N was applied in three splits: at the time of planting, at the knee-height stage, and at silking. The crop was irrigated with 50 mm water which was scheduled at IW/CPE (irrigation water/cumulative pan evaporation ratio) of 1.0. Plant biomass, yield components, and final yield were recorded. Maize crop was harvested in the last week of March during both the years. The grain and straw samples of maize in microplots were prepared and analyzed as same as rice samples described previously. Soil samples were collected in all microplots at 15 and 30 cm depth to analyze for ^{15}N to study residual soil N (15 N fertilizer not removed through the grain and residue or lost from the system), if any. The microplots were left in place throughout the study. During the second year, a new set of microplots with galvanized iron sheets measuring (1.0 × 1.0 × 0.6 m) were established to repeat the study. Micro plots established during the first year were used to study the residual effect of N applied in the preceding year.

Apparent N recovery (APR %) and agronomic N use efficiency (NUE) were calculated as per the difference method using the total plant N uptake at physiological maturity.

$$\mathrm{APR}(\%) = \frac{N_{\mathrm{f}} - N_{\mathrm{uf}}}{N_{\mathrm{a}}} \times 100, \tag{1}$$

where $\mathrm{N_f}$ and $\mathrm{N_{uf}}$ were total N uptake in fertilized and unfertilized plots (kg ha^{-1}), respectively, and $\mathrm{N_a}$ is the total amount of fertilizer N applied (kg ha^{-1}).

$$\mathrm{NUE}\ (\mathrm{kg\ grain\ kg\ N\ applied}^{-1}) = \frac{GY_{\mathrm{f}} - GY_{\mathrm{uf}}}{N_{\mathrm{a}}}, \tag{2}$$

where $\mathrm{GY_f}$ and $\mathrm{GY_{uf}}$ were the grain yield in fertilized and unfertilized plots (kg ha^{-1}), respectively, and $\mathrm{N_a}$ is the total amount of fertilizer N applied (kg ha^{-1}).

The percentage of plant N derived from fertilizer were calculated by the following Eq. (3) and (4) (Safo 1987; Malhi et al. 2004). Where $\mathrm{N_{dff}}$ is the percentage of total N in soil or plant tissue derived from the ^{15}N-labeled urea, and $\mathrm{N_{dfs}}$ is the percentage of N from soil. TN is the total N in plant part or soil, kg ha^{-1}; $\mathrm{A_u}$, $\mathrm{A_{uf}}$, and $\mathrm{A_f}$ are the atom % ^{15}N in the labeled urea fertilizer (5 %), plant part or soil receiving no ^{15}N (equals to natural abundance), and plant or soil receiving ^{15}N, respectively.

$$\begin{aligned} \mathrm{N_{diff}}(\%) &= \frac{(At\%\ 15N\ excess\ of\ total\ N\ in\ plant)}{(At\%\ 15N\ excess\ of\ total\ N\ in\ fertilizer)} \times 100 \\ &= \frac{(A_{\mathrm{f}} - A_{\mathrm{uf}})}{(A_{\mathrm{u}} - A_{\mathrm{uf}})} \times 100 \end{aligned} \tag{3}$$

$$\mathrm{N_{dfs}} = \mathrm{TN} - \mathrm{N_{diff}}. \tag{4}$$

The percentage of recovery of ^{15}N-labeled urea (REN) in the plant parts or remaining in the soil derived at the end of the crop growing season by the isotopic method was calculated using the following formula (Hauck and Bremner 1976; Bronson et al. 2000) where F is the amount of fertilizer N applied.

$$\mathrm{REN}\ (\%) = \frac{TN \times \%N_{\mathrm{diff}}}{F} \times 100. \tag{5}$$

Leaching

Suction lysimeters (soil solution access tubes) model-201 manufactured by Irrometer company, California, USA, were installed vertically to a depth of 45 cm to collect soil pore water samples in each microplot. A suction lysimeter consisted of a porous cup attached to a polyvinyl chloride (PVC) pipe, which allowed the water in the cup to be pumped out. The percolation water in flooded treatments was sampled for every 10 days during the rice season with a vacuum pump, while for aerobic rice plots samples were collected after rainfall events of more than 30 mm. The rate of water percolated out of root zone in flooded treatments was measured using lysimeters throughout the crop growth period as described by Bethune et al. (2001). In aerobic plots, deep percolation beyond the root zone was estimated using the water balance method (Willis et al. 1997). Nitrogen leaching loss was computed by multiplying $\mathrm{NO_3}^-$ and $\mathrm{NH_4}^+$ concentrations in the soil solution below the root zone with the total volume of water percolating out of the root zone per hectare. Percentage of fertilizer N lost through leaching was estimated by measuring ^{15}N in the leachate samples.

Statistical analysis

All the data on yield, yield attributes of rice and maize, and N uptake were analyzed with IRRISTAT for windows developed by International Rice Research Institute (IRRI), Philippines, consisted of analysis of variance (ANOVA), with rice establishment method and N levels as main and sub treatments, respectively (Bartolome et al. 1999). Wherever the treatments were found significant, pair wise testing with t test was performed among the main and subplot treatments. The level of confidence was set at 95 %.

Results

Grain yield

As expected, significant differences were observed between grain yields of aerobic and flooded rice plots. In aerobic rice plots, grain yields were significantly lower than yields in flooded rice. However, in both establishment methods grain yields increased significantly with the N application rates for both the years (Table 2). The increase in average yield under flooded method was 39.0 and 15.4 % more over aerobic method during 1st and 2nd years, respectively. Response to applied N was more conspicuous in flooded rice compared to aerobic rice. Mean yield increase across both the years was 32, 77 and 96 % in aerobic rice and 41, 94 and 112 % in flooded rice at the 60, 120, and 180 kg N ha^{-1} application rates compared to no N application Table 2).

Maize grown after aerobic rice, however, yielded significantly higher in both years. The yield increase in maize grown after aerobic rice was 5.8 and 5.3 % during 2009–10 and 2010–11, respectively. Incremental application of N rates to preceding rice crop has not influenced the maize yields (Table 3).

Nitrogen uptake

Average total uptake of N at physiological maturity under different treatments ranged from 50.0 and 60.7 kg ha^{-1} at 60 kg N rate to 72.0 and 98.6 kg ha^{-1} at 180 kg N rate in aerobic rice treatments during 2009 and 2010, respectively, while it was 80.5 and 74.6 kg ha^{-1} at 60 kg N to 120.6 and 123.5 kg ha^{-1} at 180 kg N in flooded treatments during 2009 and 2010, respectively (Table 2). The total N uptake was higher by 61.0, 71.0, and 67.5 % in flooded rice compared to aerobic rice at 60, 120, and 180 kg N application, respectively, in the year 2009, while the increase was 22.9, 20.0, and 25.3 % during 2010, indicating the enhanced response to increased N applications in flooded rice. In both rice growing years (2009 and 2010), significant ($P < 0.001$) difference was observed between rice establishment methods and N application rates.

Nitrogen recovery efficiency

Method of establishment has a profound effect on apparent N recovery (APR) and N use efficiency (NUE) in rice. The APR of applied urea fertilizer ranged from 21.1 to 26.6 % in 2009 and 19.8–33.7 % in 2010 under aerobic rice system (Fig. 1). Whereas, APR in flooded plots, ranged from 36.4 to 45.3 % in 2009 and 37.3–45.8 % in 2010 using the difference method. The NUE (kilogram of grain produced per kilogram of N applied) was significantly lower in both years in aerobic plots (13.2 kg kg^{-1}) compared to flooded plots (20.7 kg kg^{-1}) and ranged from 9.8 to 16.4 in aerobic rice and 17.4–23.4 in flooded rice systems (Fig. 2).

Table 2 Total plant N, Plant N derived from labeled fertilizer (N_{dff}), Plant N derived from soil (N_{dfs}), and residual soil ^{15}N in rice during 2009–10

Rice establishment method	N applied (kg ha^{-1})	Yield (t ha^{-1})		N uptake by rice plant (kg ha^{-1})		N_{dff} (kg ha^{-1})		N_{dfs} (kg ha^{-1})		Residual soil ^{15}N (kg ha^{-1})		Unaccounted ^{15}N (kg ha^{-1})	
		2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Aerobic rice	60	2.74	3.34	50.0	60.7	8.8	14.5	41.2	46.2	11.4	12.6	38.7	31.5
	120	3.45	4.72	64.0	89.3	21.8	32.2	42.2	57.1	25.4	28.6	69.5	54.0
	180	3.85	5.19	72.0	98.6	30.1	45.7	41.9	52.9	42.0	47.1	97.9	76.9
Flooded rice	60	4.36	4.00	80.5	74.6	18.7	17.5	61.8	57.1	14.2	14.7	26.1	26.8
	120	5.86	5.68	109.4	107.2	42.5	40.7	66.9	66.5	28.4	27.9	45.3	47.2
	180	6.21	6.37	120.6	123.5	58.7	56.1	61.9	67.4	48.2	51.4	63.9	62.4
ANOVA													
Method (M)	–	***	***	***	***	***	***	***	**	**	NS	***	***
N levels (N)	–	***	***	***	***	***	***	NS	NS	***	***	***	***
M × N	–	**	NS	***	NS	***	NS	NS	NS	NS	NS	***	***

NS non-significant ($P > 0.05$)

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Table 3 Recovery of ^{15}N-enriched fertilizer applied to rice by maize and ^{15}N in soil during 2009–10 and 2010–11

Rice establishment method	N applied to maize (kg ha^{-1})	Yield (t ha^{-1})		N uptake by maize plant (kg ha^{-1})		N_{dff} (kg ha^{-1})		N_{dfs} (kg ha^{-1})		Residual soil ^{15}N (kg ha^{-1})	
		2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
AR-60 N-M-120	120	5.90	6.47	135.4	151.1	1.94	2.34	133.5	148.8	8.2	10.2
AR-120 N-M-120	120	5.88	6.51	139.8	155.3	4.93	5.41	134.9	149.9	19.7	24.9
AR-180 N-M-120	120	6.15	6.73	147.3	162.3	8.18	8.46	139.1	153.8	32.0	39.3
FR-60 N-M-120	120	5.47	6.02	121.7	136.0	1.82	2.35	119.9	133.7	10.5	11.4
FR-120 N-M-120	120	5.72	6.31	130.2	146.1	4.01	4.61	126.2	141.5	21.6	23.5
FR-180 N-M-120	120	5.77	6.42	133.3	150.2	6.52	7.08	126.8	143.1	31.4	42.0
ANOVA											
Method (M)	–	*	*	*	**	***	*	*	**	*	NS
N levels (N)	–	NS	NS	NS	*	***	**	NS	NS	**	***
M × N	–	NS	NS	NS	NS	**	NS	NS	NS	*	NS

NS non-significant ($P > 0.05$), *FR* flooded rice, *AR* aerobic rice

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

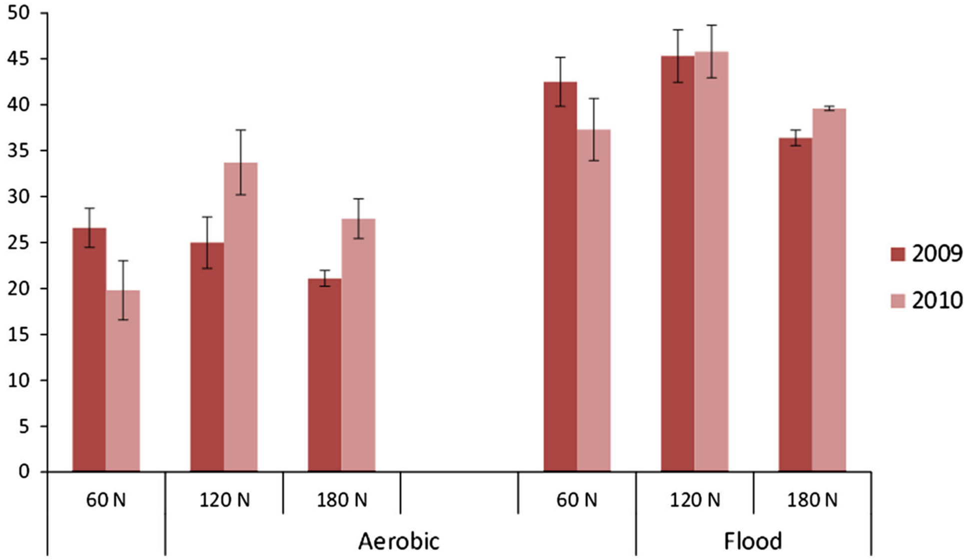


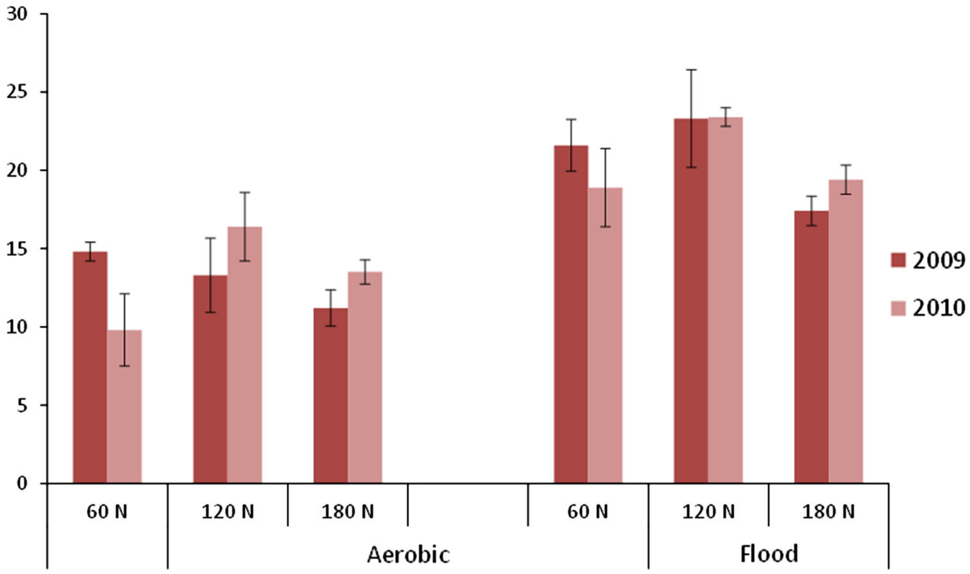
Fig. 1 Apparent N recovery (%) of rice as influenced by N rates under aerobic and flooded conditions. *Bars* indicate the standard error

The recovery of fertilizer N applied to rice was studied using ^{15}N method in grains, straw, weeds of rice, and the subsequent maize crop. In the rice season, during both the years, the fertilizer N uptake in grain and straw was higher in flooded rice (18.7–58.7 kg ha^{-1} and 17.5–56.1 kg ha^{-1} in 2009 and 2010, respectively) compared to aerobic rice (8.8–30.1 kg ha^{-1} and 14.5–45.7 kg ha^{-1} in 2009 and 2010, respectively). The uptake of fertilizer N increased with increased rate of N. However, the percent uptake was the highest at the applied N rate of 120 kg N ha^{-1} from both the systems. The 2-year-average fertilizer N uptake was 11.7, 27.0, and 37.9 kg ha^{-1} from plots that received 60, 120, and 180 kg, respectively, in aerobic rice. The corresponding uptakes recorded were significantly higher in flooded plots (18.1, 41.6 and 57.4 kg ha^{-1}, respectively).

Soil nitrogen contribution to rice crop

Crop demands for N can be met from application of inorganic fertilizer or through mineralization from soil organic pool. From the experimental results, it was evident that mineralized N from the soil organic matter was the main source in rice. Unlabeled N from soil mineralization accounted for 67.4–62.8 % of the total N in the crop in aerobic and 61.4–62.6 % in flooded rice during 2009 and 2010, respectively, which indicated that the average

Fig. 2 Nitrogen use efficiency (kg grain kg N applied^{-1}) of rice as influenced by N rates under aerobic and flooded conditions



quantities derived from soil were 41.8 kg in aerobic and 63.5 kg in flooded rice during 2009 and 52.0 and 63.7 kg in 2010, including the residual N received from 2009 application (Table 2). There were no significant differences observed in soil N contributions across N rates indicating that the rice crop obtained similar amounts of N from soil irrespective of N rates. These results confirm the importance of soil as a source of N, even in tropical soils with typical organic carbon contents around 0.50 %, and soil N from previous fertilizer applications.

Nitrogen recovery in soil between rice harvest and maize planting

After the harvest of rice crop in R-M rotation, a significant amount of fertilizer N was recovered in the surface 30 cm soil in both the systems, potentially available for subsequent crops. In 2009, flooded system recorded significantly higher amount of measured ^{15}N (14.2–48.2 kg ha^{-1}) compared to aerobic rice system (11.4–42.0 kg ha^{-1}). In 2010, in flooded rice plots, 14.7–51.4 kg ha^{-1} of ^{15}N was recovered in the soil. In aerobic rice, in 2010, 12.6–47.1 kg ha^{-1} of fertilizer N was recovered (Table 2).

Nitrogen recovery by weeds

During crop growth period, seven weed species comprising four monocots and three dicots were observed. *Echinochloa colona* (27 %), *Cynodon dactylon* (4.5 %), *Cyperus rotundus* (21 %), *Dactyloctenium aegyptium* (6.4 %), *Trianthema portulacastrum* (19 %), *Amaranthus viridis* (5.5 %), and *Eclipta alba* (16.6 %) were the predominant weeds in aerobic system, while *Echinochloa colona* (20 %), *Cynodon dactylon* (30 %), *Cyperus rotundus* (36 %), Monocharia vaginalis (4 %), Ludwigia longifolia (5 %), and Eclipta alba (5 %) are the predominant weeds in flooded rice. As two-hand weedings coupled with one pre-emergence herbicide was applied in both the systems not much weed population was observed. Further during the second year of the study due to proper weed control measures adopted during 1st year of study the weed biomass is still less compared to 1st year. During both the years, rice establishment methods and N levels influenced the weed dry matter significantly and the interaction was also found to be significant between rice establishment methods and nitrogen levels. In aerobic rice significantly higher weed dry matter production was observed compared to flooded rice. Weed dry matter increased significantly up to 180 kg N ha^{-1} during both the years of the study. The average fertilizer recovery by weeds in both years of the study was highest in aerobic rice with recoveries ranging from 0.6 to 1.3 % during 2009 and 0.62–0.71 % during 2010, respectively (Table 3), while it was 0.02–0.11 % during 2009 and 0.02–0.05 % in flooded rice. Aerobic rice establishment method presented a unique situation where weed proliferation was significant. In flooded situations, weeds were prevented due to continuous submerged conditions. The recoveries of ^{15}N in the weeds were, therefore, significantly higher in aerobic rice during both the years compared to flooded rice.

Nitrogen recovery in leachates

The total losses of applied fertilizer through leaching in aerobic system ranged from 1.2 to 4.3 % during 2009 and 1.7–5.1 % in 2010 compared to 1.6–5.0 % in 2009 and 1.8–5.6 % in 2010 under flooded rice system (Table 3). Of the total N leached over the 2 years, average fertilizer N leached was determined to be between 23 and 88 % in aerobic rice and 24–93 % in flooded rice. The contribution of applied fertilizer in inorganic N leaching increased with increased N rate applied under both the systems.

The ^{15}N-labeled urea not accounted in soil plant system at the harvest of rice varied between 38.7 and 97.9 kg ha^{-1} in 2009 and 31.5 and 76.9 kg ha^{-1} in 2010 in aerobic rice; in flooded rice, it was found to be varying between 26.1 and 64.0 kg ha^{-1} in 2009 and 26.8 and 62.4 kg ha^{-1} in 2010, indicting huge amounts of fertilizer N lost from system and envisaging the need to develop best N management practices for both aerobic and flooded rice systems.

Nitrogen recovery in maize from ^{15}N applied to rice

The recovery of fertilizer N applied to rice in maize was studied to observe the residual N contribution in both establishment methods. Average recoveries of 5.0 kg ha^{-1} (range from 1.9 to 8.2 kg ha^{-1}) in maize followed by aerobic rice and 4.1 kg ha^{-1} (range from 1.8 to 6.5) in maize followed by flooded rice were recorded during 2009–10 (Table 4). The results of the ^{15}N analysis in maize samples, during 2010–11, revealed that in maize followed aerobic rice, 2.3–8.5 kg ha^{-1} fertilizer N was recovered. Similarly, maize followed by flooded rice, 2.4–7.1 kg ha^{-1} fertilizer N applied to rice was recovered.

Nitrogen recovery in soil between maize harvest and rice planting

The soil samples after the harvest of maize were analyzed for ^{15}N. Average recoveries of 21.2 kg ha^{-1} (range from 10.5 to 31.4 kg ha^{-1}) in flooded R-M system and 20.0 kg ha^{-1} (range from 8.2 to 32.0) in aerobic R-M plots were recorded during 2009–10 (Table 4). The results of the soil sampling in maize—during 2010–11—revealed that in flooded plots, 11.4–42.0 kg ha^{-1} fertilizer N was recovered. Similarly, maize followed by aerobic rice, 10.2–39.3 kg ha^{-1} fertilizer N was recovered in the soil. Overall, soil recovery studies showed that significant fraction of the applied inorganic fertilizers were recovered in the soil indicating the potential for replenishment of soil organic N pools and maintenance of soil fertility status.

Nitrogen recovery in succeeding crops

Determination of the amount of residual N credited from the first crop to the subsequent crop is essential to determine the supplemental N needed for the subsequent crop in a cropping sequence. After the harvest of the rice crop, average recovery of N by the subsequent maize crop from applied N to the rice crop in both the systems ranged from 2.0 to 8.0 kg ha^{-1} (3.3–4.5 %). However, maize crop that followed aerobic rice showed the highest utilization of residual fertilizer N (1.9–8.2 kg ha^{-1} during 2009–10 and 2.15–7.88 kg ha^{-1} during 2010–11) compared to flooded rice (1.8–6.5 kg ha^{-1} and 2.18–6.6 during 2009–10 and 2010–11, respectively) (Fig. 3). The fraction of fertilizer recovered in the third and fourth crops in the sequence was very low. The third season recoveries (from rice) ranged from 0.7 to 1.53 %, and the fourth season (maize) recoveries ranged from 0.27 to 0.38 %, indicating that most of the fertilizer N was recovered by maize in the second growing season. The residual N data showed that the recoveries by subsequent crops after rice in both aerobic

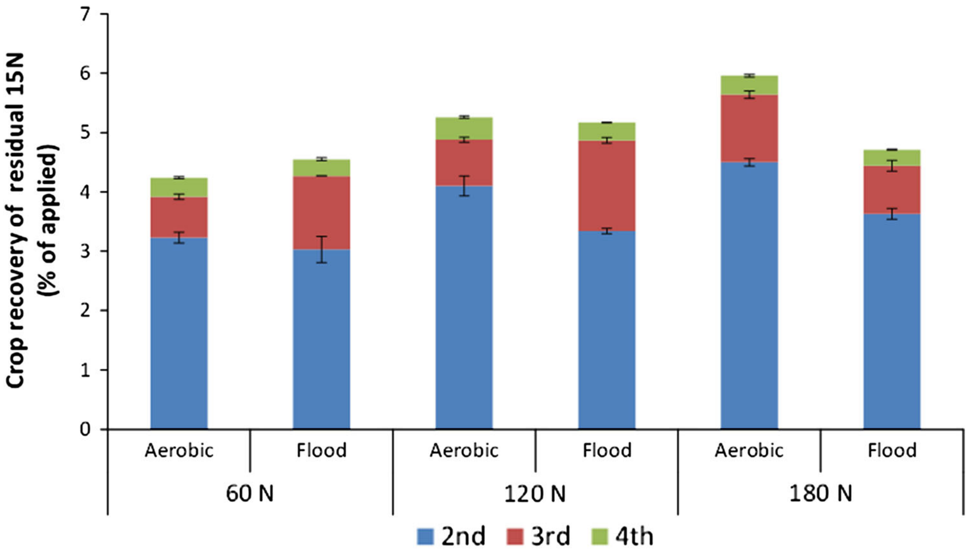
Table 4 Fertilizer ^{15}N leaching and weed uptake of ^{15}N during rice crop in 2009 and 2010

Treatment	N applied (kg ha^{-1})	$^{15}\text{NO}_3$-N (kg ha^{-1})		$^{15}\text{NH}_4$-N (kg ha^{-1})		% of ^{15}N fertilizer N leached		Weed biomass (g/m^2)		^{15}N uptake by weeds (kg ha^{-1})		% of fertilizer ^{15}N lost through weeds	
		2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Aerobic rice	60	0.51	0.66	0.18	0.37	1.2	1.7	41.1	34.6	0.36	0.38	0.60	0.64
	120	1.84	2.81	0.71	1.46	2.1	3.6	47.5	37.2	0.78	0.86	0.65	0.71
	180	5.66	6.55	2.00	2.56	4.3	5.1	53.3	40.2	2.34	1.12	1.30	0.62
Flooded rice	60	0.27	0.31	0.67	0.75	1.6	1.8	12.5	11.9	0.02	0.02	0.04	0.04
	120	1.47	1.20	2.40	3.03	3.2	3.5	14.9	15.6	0.06	0.04	0.05	0.03
	180	3.17	3.60	5.75	6.55	5.0	5.6	18.4	19.2	0.11	0.05	0.06	0.03
ANOVA													
Method (M)	–	***	**	***	***	*	NS	***	***	***	***	***	***
N rates (N)	–	***	***	***	***	***	***	***	***	***	***	***	NS
M × N	–	***	***	***	***	NS	NS	***	***	***	***	***	NS

NS non-significant ($P > 0.05$)

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Fig. 3 Average ^{15}N in crop derived from application of N labeled fertilizer to rice under different nitrogen rates in subsequent growing seasons. The legend refers to the number of growing seasons after rice



and flooded systems were very small and will not be adequate to meet N requirements in any substantial way.

Discussion

Growing rice under flooded irrigation usually takes twice as much water compared to other major crops such as wheat and maize (Tuong and Bouman 2003). The present studies on the response of aerobic rice to incremental rates of N in comparison with flooded rice demonstrated larger differences in yield and N recoveries, which were closely related to differences in N dynamics observed in both the systems.

Fertilizer N use efficiency in rice was estimated by both N difference (APR) and ^{15}N isotopic methods. Values of FUE estimated by the N difference method were higher than the isotopic method mainly due to inclusion of residual N and due to the overall effect of unlabeled fertilizers applied including the effect of previous year's applications. Several previous studies also reported lower N recoveries estimated by the isotopic method compared to the N difference method (Schnier 1994; Cassman et al. 1993; Bronson et al. 2000; Singh et al. 2001; Belder et al. 2005). The crop recovery of applied N as estimated by isotopic method was very low in aerobic soils (14.7–26.8 %) compared to flooded rice. Reductions in N recovery in rice, when converted to water-saving systems, were also observed by Eriksen et al. (1985) and Belder et al. (2005). In the present experiment, from the amount of fertilizer N applied, 21.0 % was taken up by the plants, 22.4 % was left in the soil, and 53 % was unaccounted for indicating that N uptake was one of the major limiting factors in decreasing dry matter and subsequently the grain yields. Belder et al. (2005) also noticed higher losses of applied N in aerobic rice compared to traditional flooded conditions mainly due to gaseous N losses due to rapid nitrification–denitrification processes. The apparent N recovery in both the systems was higher at 120 kg N rate than at 180 kg N, indicating that the efficiency of any input decreases with increased rate of application, because other factors such as water and other nutrients becomes limited (De Wit 1992).

The N transformation in flooded rice is altogether different from aerobic rice system, even though the forms of N present under both the systems are similar. However, the relative magnitudes of NO_3^- and NH_4^+ forms are quite different between the two systems; NH_4^- N found to be the most dominant form in flooded rice systems due to anaerobic conditions. The main N transformations in both the systems include mineralization, immobilization, ammonia volatilization, nitrification–denitrification, and leaching.

In flooded soils, due to submerged conditions, lower mineralization rates are expected as a result of slower breakdown of soil organic matter compared to upland aerobic systems (Villegas-Pangga et al. 2000; Buresh et al. 2008). Even the immobilization rates are also quite low in flooded systems due to low energy requirements of anaerobic microorganisms resulting in a high net mineralization rates. In the present study, relatively higher amount of soil N (56–67 kg) was accumulated by the crop grown in flooded conditions compared to aerobic rice (41.2–56.1 kg ha^{-1}), indicating that higher net mineralization rates might have been the reason behind the higher uptake in flooded rice. With regards to fertilizer N, high water solubility of urea in flooded soils may be the reason behind the high fertilizer N uptake in flooded rice plants. Due to the weak adsorption of urea by soil compared to NH_4^+ (De Datta 1981; Safeena et al. 1999) more applied urea was found in the solution phase than on the solid phase, resulting in greater absorption of N form urea by rice plants from flooded soil than plants in a non-flooded aerobic condition.

Poor N use efficiency in aerobic rice compared to flooded systems was mainly due to increased N losses in the system. In the present experiment, the unaccounted N ranged between 43 and 65 %, showing that most of the applied fertilizer N may have been lost from the soil plant system in gaseous form. Similarly, in flooded rice 34–45 % of fertilizer N was unaccounted. In the aerobic rice, nitrification rates are generally higher due to abundant availability of oxygen. The NO_3^- so produced will either be taken up by the plant or be lost to atmosphere as N_2 gas, if anaerobic conditions occur (Buresh et al. 2008). In the present study, during irrigation and heavy rainfall events, the aerobic soils experienced frequent transitions between aerobic and anaerobic cycles, which may have led to increased N losses. Therefore, we conclude that denitrification is probably the most relevant process contributing to the loss of N in aerobic rice. Even though flooded rice plots were kept submerged throughout the crop growth, mid-season aeration for promoting high tiller production might have resulted in considerable denitrification losses.

Nitrate–N in aerobic rice and NH_4^+-N in flooded rice were the predominant forms of N leaching. Leaching losses increased in both systems with increased N rates and there were no differences in the leaching losses derived from the fertilizers between the two systems. A number of other studies also reported considerable losses through leaching in paddy soils under both aerobic and flooded systems (Pathak et al. 2004; Zhou et al. 2009; Linquist et al. 2011; Peng et al. 2011).

Weed control is another key factor for getting optimum yields in aerobic rice. Yield losses up to 50–91 % due to dry tillage, alternate wetting, and drying conditions in aerobic rice were reported (Fujisaka et al. 1993; Rao et al. 2007; Singh et al. 2008). In the present experiment, up to 1.3 % of applied N was taken up by the weeds. The higher growth and N accumulation by weeds in aerobic rice is also one of the reasons for yield penalty in aerobic system.

The response to N in aerobic rice between 2 years of study was significant. The difference can be explained by the fact that during 2010, monsoon rains were well distributed and the soil moisture content was mostly maintained near field capacity throughout the crop growth. Better weed control measures using chemical herbicides were adopted, and the average N uptake and N recovery by weeds was decreased to 0.61 % compared to 0.85 % during 2009.

In the present experiment, residual N recoveries in succeeding crops up to four seasons were determined. The results showed that the recovery of ^{15}N in the subsequent crops was very low (4.2–6.0 %). Most of the residual N fertilizer recovery occurred in the maize crop grown after rice (3–4.5 %), and decreased to 1 % or less in the subsequent growing seasons, indicating poor utilization of residual N. Total recovery of fertilizer N would increase to 26.1 and 37.0 % compared to the single-season value of 21.0 and 32.2 % in aerobic and flooded rice, respectively, once the residual ^{15}N is also accounted for. No significant difference was observed in the subsequent crop recoveries between aerobic and flooded rice system. Similar low recoveries in succeeding crops in cropping system trials were reported by Shinde et al. 1985; Shivananda et al. 1996; Ichir et al. 2003; Sampaio et al. 2002; Dourado-Neto et al. 2010 in different cropping systems. Immobilization of fertilizer N in soil organic matter that mineralizes very slow (Ichir et al. 2003) and poor synchronization between mineralization of ^{15}N-labeled organic residue and crop uptake (Macdonald et al. 2002) resulted in suppressed utilization of residual N from the previously applied N. Since the residual effects are of small order, the scope of reducing N dosages for succeeding crops in the sequence keeping in view the residual N from previous application is limited.

Conclusions

The concept of aerobic rice development is to sustain the rice production in scarce water situations, yet producing 80–90 % of yield attainable under traditional flooded rice system. The present study on response of aerobic and flooded rice to N rates showed positive response for increased N application under both the systems. However, the response to the applied N fertilizer was significantly lower in aerobic rice than in flooded rice. The apparent N recovery calculated by N difference method and N fertilizer use efficiency were considerably low in aerobic rice because of the reduction in N uptake rate by aerobic rice. It suggested that a large amount of fertilizer N loss occurred from soil plant system (49–59 %) for aerobic rice. Only a small proportion of the fertilizer N applied (4.2–6.0 %) to rice was recovered in succeeding maize indicating reduced residual effect under both flood and aerobic rice system. Even though residual effects were of small order, fertilizer N recoveries in soil were as high as 42 kg ha^{-1} after fourth season indicating that the contribution of applied fertilizer to the maintenance of soil fertility. From this study, it was clearly evident that optimization of nitrogen fertilizers in both the establishment methods can reduce significantly residual N, loss of N, and minimize environmental impact. Further research should focus mainly on studying the physiological responses of aerobic rice under this new method of establishment. The research should also focus on optimization of water and nitrogen input, amount, timing, and methods of application to improve its efficiency to make it more adaptable by the farmers.

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